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Power Supply Bypassing for High-Voltage Operatinal Amplifiers

POWER SUPPLY BYPASSING FOR HIGH-VOLTAGE OPERATIONAL AMPLIFIERS

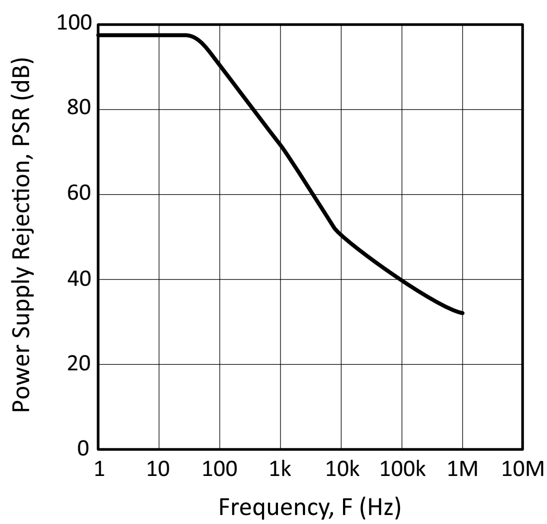
With the introduction of Apex's high-voltage amplifiers like PA89 and PA99, new issues arise in the realm of circuit board layout and power supply bypassing. Working with these amplifiers, designers quickly realize that the same rules do not apply between bypassing high- and low-voltage Op-Amps. This applications information is meant to assist in designing the bypass system in a high-voltage operational amplifier circuit and choosing the perfect capacitors for use in such designs.

THE NEED FOR POWER SUPPLY BYPASSING

Before finding a couple of high-voltage capacitors and tacking them onto your supply rails, it is vital to realize the purpose of these capacitors and what we need them to do.

Power supply bypass capacitors are there to stabilize the supply voltages of a circuit. Logically, the next question to answer would be, "What causes supply voltages to change?" This list can go on, but the most common reasons for changing supply voltages are power interruptions, high-frequency voltage/current spikes, and high-current draws.

Figure 1: Power Supply Rejection Chart of PA89



The first two entries on the list can be lumped into one category called "high-frequency events." One close look at the datasheet for PA89 yields the Power Supply Rejection chart. As the frequency increases, power supply rejection falls off rather quickly. For example, if the power supply rail experiences a 100 kHz spike, then as much as 1% of that high-frequency voltage change will show up on the output. Many designs cannot tolerate this kind of distortion. Even the designs that can tolerate such distortion will suffer from stability issues and from the risk of damaging the internal components of the op-amp due to over-voltage. This is why Apex's recommendation is: ALWAYS BYPASS!

The third entry on the list, high-current draws, has earned a special place on many Apex evaluation boards. For our high-current amplifiers, we design our boards with electrolytic capacitors of at least 10µF per amp of output current. These caps will store plenty of charge from the power supplies, and then release that charge when the amplifier needs it in the form of output current. For this reason, these capacitors are generally called “bulk storage” capacitors.

When considering the PA89 and PA99, these amps are limited to 100 mA and 50 mA of output current, respectively. Following the 10µF rule above, this would necessitate a 1 to 0.5µF cap of bulk storage. For such low current draws, these capacitors would not add very much benefit to the circuit. Why not? Because the high-frequency bypass capacitors will likely be close enough to these capacitance values, that they can serve both functions. While the bulk storage caps may not be necessary for low-current applications, the high-frequency bypasses are crucial.

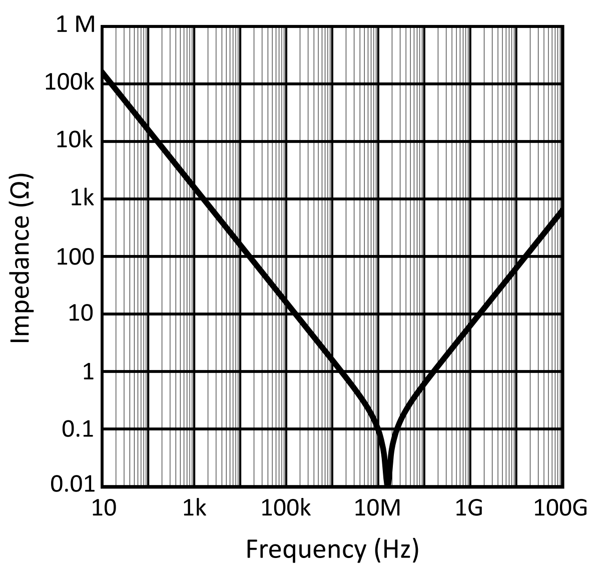
WHAT TO LOOK FOR

High-frequency, high-voltage bypassing is the subject of this application note. On almost every Apex datasheet, you will see a call for “0.1 to 1µF ceramic capacitors directly at the supply pins.” These are the high-frequency bypass capacitors. The intent of these caps is to “fill in” that area of the Power Supply Rejection chart where the amplifier simply cannot block high-frequency changes. Therefore, these caps need to meet certain criteria to adequately protect your high-voltage amplifier:

LOW ESL

Capacitors are not perfect; lower-quality capacitors have some trace amounts of resistance and inductance that will change their properties in different applications. Inductance, in particular, eliminates the advantage of high-frequency bypass capacitors. Even picoHenries of inductance, at high frequency, can raise the impedance of the bypass caps to the point where there is nothing stopping a high-frequency event from damaging the amplifier. Consider figure 2, which shows the impedance of a 0.1µF capacitor with 10 mΩ and 1 nH of parasitics. After the resonant frequency of 16 MHz, the capacitor no longer acts like a capacitor. Instead, it lets high-frequency spikes straight into the supplies of the amplifier. Therefore, the high-frequency capacitors MUST be low ESL-type and they MUST be mounted as close as possible to the amplifier supply pins (long traces have inductance, too!).

Figure 2: Impedance of a 100nF capacitor with 10 mΩ and 1 nH



HIGH-VOLTAGE RATING

This should be a no-brainer. Electrically, the bypass caps go directly across the supply terminals, so they must be able to withstand whatever voltage the supply is. Unfortunately, 0.1 to 1µF caps with voltage ratings of 2.5kV are hard to find, at least at the time this application note was written. For a discussion of parallel vs. series configurations in order to achieve these ratings, see the below sections.

LOW TEMPERATURE COEFFICIENT

The bypass capacitors will be mounted as close as possible to the power amplifier, which will inevitably get hot. Therefore, it is in the interest of the design to get capacitors that are stable over a wide temperature range. If you are still not convinced that a low temp co is vital, consider the energy equation of a capacitor:

$$U = \frac{CV^2}{2}$$

Let’s say a Y5V-type capacitor is used for bypassing the PA89 with ±600V supplies. Y5V capacitors can drop their capacitance by as much as 82% within its temperature range. Initially, the bypass capacitor is 0.1µF. Therefore, the capacitors are storing 18 mJ of energy each. Then, the PA89 heats up the surrounding PC board, and the temperature of the capacitors raises to 85°C. As the capacitance drops to 0.018µF, the energy balance theoretically forces the voltage up to 1400V each! This would surely destroy the amplifier, which has a maximum rail-to-rail voltage of 1200V. In reality, the capacitors are connected to a power supply and an amplifier, which will dissipate most of the extra energy in the time that it takes for the capacitors to heat up.

LOW dC/dV

For the same reason as temperature coefficients, the capacitance should be stable with voltage. This is especially true for high-voltage bypass capacitors. Capacitance values are measured at 0V, and the values may decrease significantly with applied voltage. As a guideline, larger package styles tend to have a lower dC/dV.

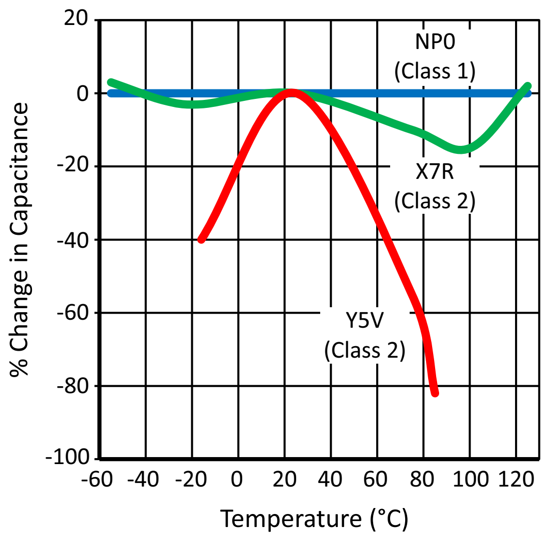
CAPACITOR CLASSES

Luckily, the above qualities are already grouped together into categories called capacitor classes, which takes much of the effort out of searching for the perfect capacitor. For ceramic capacitors, three standard classes exist:

CLASS 1 CERAMIC CAPACITORS

Class 1 caps have the lowest temperature coefficients and greatest stability, as well as very low loss and ESL. The more commonly used class 1 capacitors are C0G (also called NP0), which will have a temp co between ±30ppm/°C. This is more than enough temperature stability for Apex high-voltage bypassing requirements. Unfortunately, class 1 caps don’t store as much energy as other capacitors. A high-capacity class 1 cap may provide 2.2nF at 1000V. Bypassing with these capacitors would take up quite a bit of room on both the PCB and the Bill of Materials.

Figure 3: Comparison of the temperature stability for typical Class 1 and 2 Ceramic Capacitors.



CLASS 2 CERAMIC CAPACITORS

Class 2 contains the next range of temperature coefficients. These capacitors are less stable than class 1, but they provide much better energy density in the trade-off. The more common types of class 2 capacitors are named X7R (or 2X1). X7R caps can change in value by up to ±15% over their temperature range of -55°C to 125°C, which is good enough for most Apex products. Be sure to check the datasheet for the tolerance over the temperature range, as some class 2 ceramic capacitors can have a tolerance as wide as 82%. Apex recommends the use of X7R's ±15% or better tolerance for all bypass requirements.

CLASS 3 CERAMIC CAPACITORS

Class 3 ceramic capacitors are not recommended for use with Apex products. In fact, these capacitors are mostly obsolete and no longer standardized.

CLASS 1 POLYPROPYLENE FILM CAPACITORS

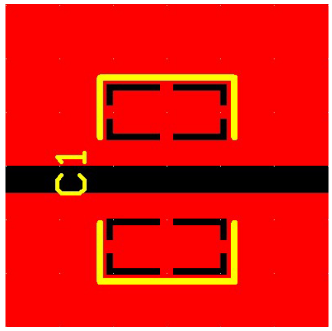
Although these are not ceramic capacitors, polypropylene (PP) capacitors offer temperature stability of around ±2.5%, comparable to class 1 ceramics. PP caps also have low ESL and dissipation factors. The main drawbacks of these capacitors are the limited temperature range and their size. The temperature may not exceed 105°C, which limits their mounting type to through-hole. Class 1 PP high-voltage bypasses are also quite large, and can take up a good chunk of the board space.

MECHANICAL CONSIDERATIONS

In all likelihood, the bypass caps you choose to implement will not be the small 0805 SMD package that solders with no problem. The high-voltage bypasses for Apex parts will generally be of size 2220 or larger, and the soldering process requires more attention. When mounting larger SMD capacitors, it is important to heat the part uniformly to avoid cracking. Small cracks within the ceramic could short out the internal layers. However, thermal relief pads are discouraged due to the increase in ESR and ESL.

Ceramics are very hard but brittle materials. These capacitors may even crack from simply flexing the board. Care must be taken that the board is secure and is not subjected to extreme stresses.

Figure 4: Do not use thermal relief pads due to the increase in parasitic R and L



GETTING THE RIGHT AMOUNT OF CAPACITANCE

Assembling bypass for the PA99 on a single 2500V supply requires a capacitor with a voltage rating of at least 2.5kV. Trying to push the capacitance up to 0.5µF makes the search quite arduous. At the time of this application note, no single commercially available X7R ceramic capacitor can do the job. This leaves the designer with two options:

PARALLEL

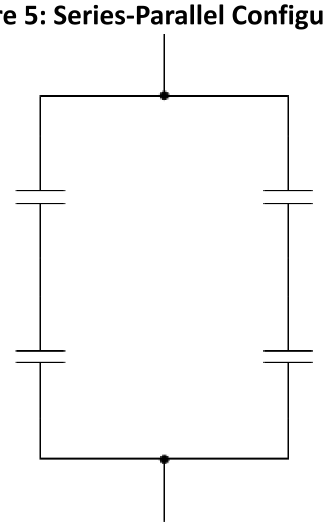
Currently, the highest capacitance for a 2.5kV ceramic X7R capacitor is around 22nF. By paralleling 5 of these capacitors together, the minimum bypassing requirement of 0.1µF can be met. The preferred 0.5µF would take around 23 caps. Parallel capacitors have the advantage that ESL and ESR are reduced, relieving some of the quality requirements.

SERIES-PARALLEL

As the voltage rating of ceramic capacitors goes down, the available energy density tends to go up. For 1.5kV ceramic X7R caps, the maximum capacitance is somewhere around 150nF. For the PA99 using symmetric 1250V supplies, one of these capacitors on either rail would suffice. However, bringing one of the rails up past 1500V requires a series-parallel technique.

The advantage of the series-parallel configuration is fewer capacitors. For the same 2.5kV, 0.5µF rating above, it can be accomplished with 14 capacitors in a 7 x (1 + 1) array. The disadvantage: placing two caps in series doubles the effective ESR and ESL.

Figure 5: Series-Parallel Configuration



HOW MUCH CAPACITANCE IS REALLY NEEDED?

The answer to this question depends largely on how you plan to use the amplifier. If the amplifier is outputting significant amounts of current, use the 10µF per amp rule above. This is based on the “Ohm’s Law” of capacitance:

$$i = C\frac{dV}{dt}$$

The 10µF rule allows for a 0.1 V/µs ripple on the power supply. If, after analyzing the power supply rejection, this ripple is too great for the design, more bypass may be required.

If the amplifier is unloaded and the output voltage does not need perfect power supply rejection, then the bypassing can be relieved down to 0.1µF. 0.1µF is the lower limit for most Apex amplifiers for stability reasons; even small power supply transients can cause the power amplifier to oscillate and become damaged.

CONCLUSION

With these guidelines, the designer is one step closer to integrating one of Apex’s high-voltage amplifiers into their board. PA89 and PA99 are unique and powerful op-amps that need special attention in the surrounding layout. For more applications help with these amplifiers and any other Apex products, contact Applications Engineering at apexanalog.com.

REFERENCES

1. Fortunato, Mark. “Temperature and Voltage Variation of Ceramic Capacitors, or Why Your 4.7µF Capacitor Becomes a 0.33µF Capacitor.” 26 Nov. 2012. Web. 01 Apr. 2016.
2. “High Temperature High Voltage Ceramic Capacitors.” KEMET Electronics Corporation. Web. 01 Apr. 2016.
3. “Multilayer Ceramic Capacitors.” Microelectronics Reliability. Cornell Dubilier Electronics, Inc. Web. 01 Apr. 2016.