ANALOG DEVICES

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APPLICATION NOTE

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Capacitor Selection Guidelines for Analog Devices, Inc., LDOs

by Glenn Morita

WHY DOES THE CHOICE OF CAPACITOR MATTER?

Capacitors are underrated. They do not have transistor counts in the billions nor do they use the latest submicron fabrication technology. In the minds of many engineers, a capacitor is simply two conductors separated by a dielectric. In short, they are one of the lowliest electronic components.

It is common for engineers to add a few capacitors to solve noise problems. This is because capacitors are widely seen by engineers as a panacea for solving noise related issues. Other than the capacitance and voltage rating, little thought is given to any other parameter. However, like all electronic components, capacitors are not perfect and possess parasitic resistance, inductance, capacitance variation over temperature and voltage bias, and other nonideal properties.

These factors must be considered when selecting a capacitor for many bypassing applications or where the actual value of the capacitor is important. Choosing the wrong capacitor can lead to circuit instability, excessive noise or power dissipation, shortened product life, or unpredictable circuit behavior.

CAPACITOR TECHNOLOGIES

Capacitors come in a wide variety of form factors, voltage ratings, and other properties to meet the requirements of diverse applications. Commonly used dielectric materials include oil, paper, glass, air, mica, various polymer films, and metal oxides. Each dielectric has a specific set of properties that allows it to meet the unique needs of each application.

There are three major classes of capacitors commonly used as voltage regulator input and output bypass capacitors: multilayer ceramic, solid tantalum electrolytic, and aluminum electrolytic.

Multilayer Ceramic Capacitor

Multilayer ceramic capacitors (MLCC) combine small size, low effective series resistance and inductance (ESR and ESL), and wide operating temperature range and are usually the first choice for use as bypass capacitors.

Ceramic capacitors are not without faults. Depending on the dielectric material used, the capacitance can shift dramatically with changes in temperature, and dc or ac bias. Additionally, because of the piezoelectric nature of the dielectric material in many ceramic capacitors, vibration or mechanical shock can be transformed into an ac noise voltage on the capacitor. In most cases, this noise tends to be in the microvolt range. However, in extreme cases, noise in the millivolt range can be generated.

Applications such as VCOs, PLLS, RF PAs, and low level analog signal chains are very sensitive to noise on the power supply rail. The noise manifests itself as phase noise in the case of VCOs and PLLs and amplitude modulation of the carrier for RF PAs. In low level signal chain applications such as EEG, ultrasound, and CAT scan preamps, noise results in artifacts displayed in the output of these instruments. In these and other noise sensitive applications, the use of multilayer ceramic capacitors must be carefully evaluated.

Taking the temperature and voltage effects is extremely important when selecting a ceramic capacitor. The Multilayer Ceramic Capacitor Selection section explains the process of determining the minimum capacitance of a capacitor based on its tolerance and dc bias characteristics.

While ceramic capacitors are not perfect, they are used in virtually every electronic device manufactured today because they result in solutions that have the smallest footprint and are the most cost effective for many applications.

Solid Tantalum Electrolytic Capacitor

The solid tantalum electrolytic capacitor offers the highest capacitance per unit volume (CV product). Only the dual layer or supercapacitors have higher CV products.

In the 1 µF range, ceramics are still smaller and have lower ESR than tantalums, but solid tantalum capacitors do not suffer as much from the effects of temperature, bias, or vibration. Tantalums cost several times as much as a ceramic capacitor, but in low noise applications where the piezoelectric effect cannot be tolerated, tantalums are often the only viable choice.

Conventional low value solid tantalum capacitors available on the market do not have low ESR because the cases used tend to be small. Large value (>68 µF) tantalum capacitors can have ESRs under 1 Ω, but they tend to be large.

Recently, a new variation of the tantalum capacitor has become available that uses a conductive polymer electrolyte instead of the normal manganese dioxide solid electrolyte. Historically, solid tantalum capacitors have suffered from limited surge current capability and required a series resistor to limit the current surges to a safe value. Conductive polymer tantalum capacitors do not suffer from the surge current limitation. ESR reduction of the capacitor is an additional benefit.

The leakage current of any tantalum capacitor is many times greater than it is for a ceramic capacitor of equal value and may render them unsuitable for extremely low current applications.

For example, a 1 µF/25 V tantalum capacitor has a maximum leakage current of 2.5 µA at rated voltage while operating at 85°C.

Several vendors offer 1 µF/25 V conductive polymer tantalum capacitors with 500 mΩ ESR in an 0805 case. While somewhat larger than the typical 1 µF ceramic capacitor in a 0402 or 0603 case, the 0805 represents a decent reduction in the size of the capacitor for applications such as RF and PLLs where low noise is the main design goal.

Because the solid tantalum capacitor has a stable capacitance characteristic with temperature and voltage bias, the selection criteria of the capacitor need only account for the capacitor tolerance, derated voltage at the operating temperature, and maximum ESR.

One drawback of the solid polymer electrolyte technology is that this type of tantalum capacitor is more sensitive to the high temperatures encountered in the lead-free soldering process. Typically, the manufacturers specify that the capacitors not be exposed to more than three soldering cycles. Long-term reliability issues can result if compliance with this requirement is ignored in the assembly process.

Aluminum Electrolytic Capacitor

Conventional aluminum electrolytic capacitors tend to be large and have high ESR and ESL, relatively high leakage current, and service lifetimes measured in thousands of hours.

OS-CON type capacitors are a technology that is related to the solid polymer tantalum capacitors and actually precede the tantalum capacitors by 10 years or more. These capacitors employ an organic semiconductor electrolyte and an aluminum foil cathode to achieve low ESR. Because there is no liquid electrolyte to dry out, the service lifetime of the OS-CON type capacitor is greatly improved compared to the conventional aluminum electrolytic capacitor.

OS-CON type capacitors capable of 125°C operation are becoming available but most are still limited to 105°C.

Although the performance of the OS-CON type capacitor is greatly improved over the conventional aluminum electrolytic, they tend to be larger and have higher ESR compared to ceramic or solid polymer tantalum capacitors. Like the solid polymer tantalum, they do not suffer from the piezoelectric effect and are suitable for use in applications where low noise is a requirement.

MULTILAYER CERAMIC CAPACITOR SELECTION

Output Capacitor

Analog Devices LDOs are designed for operation with small, space-saving ceramic capacitors, but functions with most commonly used capacitors as long as care is taken with regard to the ESR value. The ESR of the output capacitor affects the stability of the LDO control loop. A minimum of 1 µF capacitance with an ESR of 1 Ω or less is recommended to ensure the stability of the LDO.

Transient response to changes in load current is also affected by output capacitance. Using a larger value of output capacitance improves the LDO's transient response to large changes in load current. Figure 1 through Figure 3 show the transient response for an ADP151 with output capacitance values of 1 µF, 10 µF, and 20 µF, respectively.

Because the LDO control loop has a finite bandwidth, the output capacitor must supply most of the load current for very fast transients. A 1 µF capacitor cannot supply current for very long and results in a load transient of about 80 mV. A 10 µF capacitor improves the load transient to about 70 mV. Increasing the output capacitance to 20 µF allows the LDO control loop to catch up and actively reduce the load transient. The test conditions are shown in Table 1.

Table 1. Test Conditions

Condition	Value
UUT	ADP151-3.3
V_{OUT}	3.3 V
V_{IN}	5 V
Load transient	1 mA to 200 mA, 500 mA/µs
Channel 1	Load current
Channel 2	V_{OUT} (ac-coupled)

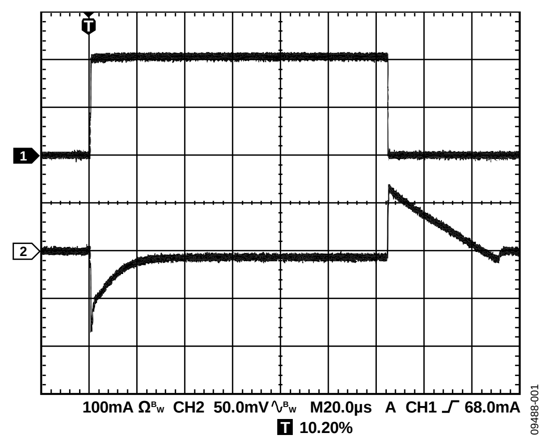

Figure 1. Output Load Transient Response, C_{OUT} = 1 µF

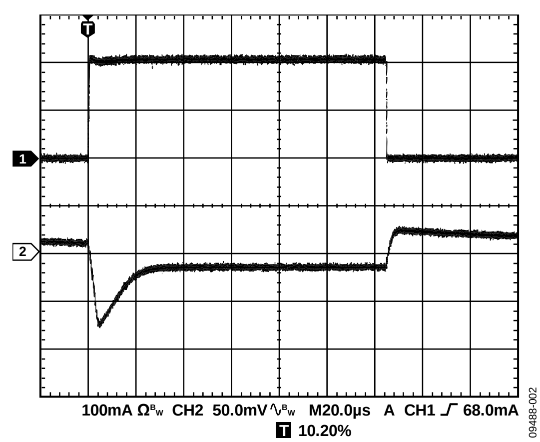

Figure 2. Output Transient Load Response, C_{OUT} = 10 µF

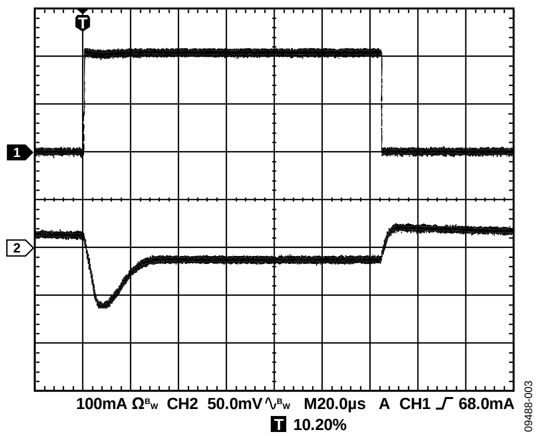

Figure 3. Output Load Transient Response, $C_{OUT} = 20\ \mu F$

Input Bypass Capacitor

Connecting a 1 µF capacitor from VIN to GND reduces the circuit sensitivity to the printed circuit board (PCB) layout, especially when long input traces or high source impedance are encountered. If greater than 1 µF of output capacitance is required, the input capacitor should be increased to match it.

Input and Output Capacitor Properties

Any good quality ceramic capacitors can be used with the LDO, as long as they meet the minimum capacitance and maximum ESR requirements. Ceramic capacitors are manufactured with a variety of dielectrics, each with different behavior over temperature and applied voltage. Capacitors must have a dielectric adequate to ensure that the minimum capacitance is provided over the working temperature range and dc bias conditions. X5R or X7R dielectrics with a voltage rating of 6.3 V or 10 V are recommended for 5 V applications. Y5V and Z5U dielectrics are not recommended, due to their poor temperature and dc bias characteristics.

Figure 4 depicts the capacitance vs. voltage bias characteristic of an 0402, 1 µF, 10 V, X5R capacitor. The voltage stability of a capacitor is strongly influenced by the capacitor package size and voltage rating. In general, a capacitor in a larger package or higher voltage rating exhibits better voltage stability. The temperature variation of the X5R dielectric is ~±15% over the −40°C to +85°C temperature range and is not a function of package or voltage rating.

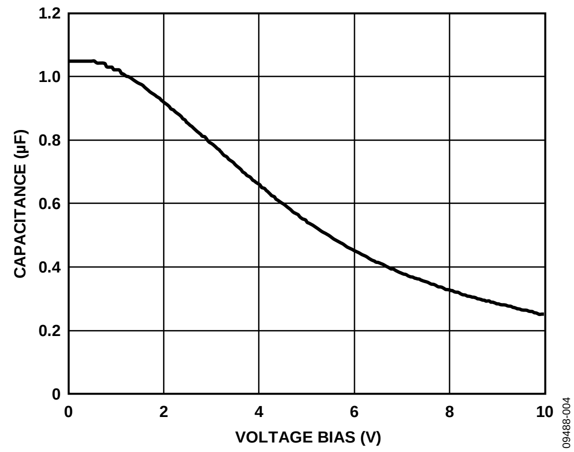

Figure 4. Capacitance vs. Voltage Bias Characteristic

Use Equation 1 to determine the worst-case capacitance when accounting for capacitor variation over temperature, component tolerance, and voltage.

$$C_{EFF} = C_{BIAS} \times (1 - TVAR) \times (1 - TOL) \quad (1)$$

where:
C_{BIAS} is the effective capacitance at the operating voltage.
$TVAR$ is the worst-case capacitance variation over temperature (as a fraction of 1).
TOL is the worst-case component tolerance (as a fraction of 1).

In this example, the worst-case capacitance (TVAR) over −40°C to +85°C is assumed to be 0.15 (15%) for an X5R dielectric. The tolerance of the capacitor (TOL) is assumed to be 0.10 (10%), and C_{BIAS} is 0.94 µF at 1.8 V, as shownFigure 4.

Substituting these values in Equation 1 yields

$$C_{EFF} = 0.94\ \mu F \times (1 - 0.15) \times (1 - 0.1) = 0.719\ \mu F$$

The LDO in this example specifies a minimum output bypass capacitance of 0.70 µF over the intended operating voltage and temperature range. Therefore, the capacitor chosen for this application meets this requirement.

SUMMARY

To guarantee the performance of an LDO, it is imperative that the effects of dc bias, temperature variation, and tolerance of the bypass capacitor be understood and evaluated for the selected capacitor.

In addition, applications where low noise, low drift, or high signal integrity is a requirement, the capacitor technology used must also be considered. All capacitors suffer from the effects of nonideal behavior but some capacitor technologies are better suited for certain applications than others.

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