Application Report
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How to Choose a TPS7B67xx-Q1 Output Capacitor

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ABSTRACT

For linear regulators, the output capacitor has a big influence on the stability and transient performance of a design. Multilayer ceramic capacitors, aluminum electrolytic capacitors, and solid tantalum-electrolytic capacitors are the three types of capacitors that are commonly used as output capacitors. This application report describes advantages and disadvantages of the three types of capacitors. This report also includes a guide for selecting a suitable output capacitor for the TPS7B67xx-Q1 family of devices.

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1 Overview

Other documents that describe the linear regulator operation and compensation theory are also available. The documents that follow are typical documents that focus on the theory of stability analysis of linear regulator:

- *Stability analysis of low-dropout linear regulators with a PMOS pass element* (SLYT194)
- *AN-1482 LDO Regulator Stability Using Ceramic Output Capacitors* (SNVA167)
- *Linear Regulators: Theory of Operation and Compensation* (SNVA020)
- *ESR, Stability, and the LDO Regulator* (SLVA115)

For linear regulators, because the output capacitors have a big influence on the stability and transient performance, selecting a suitable output capacitor to meet the system requirement is important. The three types of capacitors are commonly used as the output capacitor in linear-regulator circuit designs: multilayer ceramic capacitors, aluminum electrolytic capacitors, and solid-tantalum electrolytic capacitors. This application report describes advantages and disadvantages of the three types of capacitors. This report also includes a guide for selecting a suitable output capacitor for the TPS7B67xx-Q1 family of devices.

2 Capacitor Analysis

The ideal capacitor only stores and releases electrical energy without dissipating any power. In reality, all capacitors have imperfections within the materials of the capacitor that create resistance. These imperfections is specified as the equivalent series resistance (ESR) of a component. The ESR adds a component to the impedance. Similarly to ESR, the leads of the capacitor add the equivalent series inductance (ESL) to the component. The ESL is usually significant only at relatively high frequencies. As inductive reactance is positive and increases with frequency, it is canceled by the inductance when it is above a certain frequency capacitance.

Figure 1 shows the equivalent model. The parasitic parameters of different capacitors vary a lot which results in different performance of the linear regulator circuits. The following sections describe the detailed characteristics of the three types of capacitors.

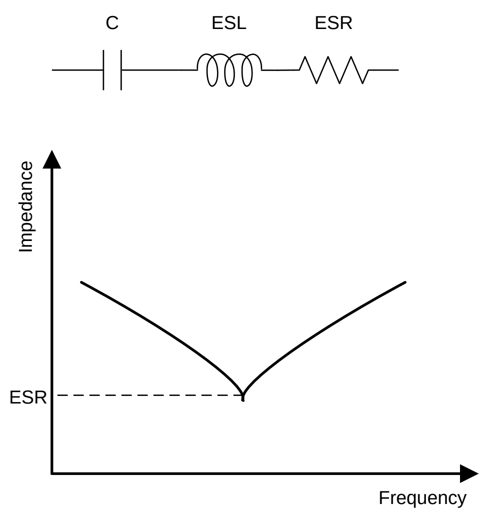


Figure 1. Equivalent Model of Actual Capacitor

2.1 Multilayer Ceramic Capacitor

Multilayer ceramic capacitors (MLCC) have many advantages such as low ESR, small size, low ESL, and a wide operating temperature range. Ceramic capacitors also have good performance in attenuation characteristics, which makes ceramic capacitor the first choice for bypass capacitors. The noise reduction performance of ceramic capacitors is also very good, because the low ESR and ESL make conducting noise to ground easy.

Although ceramic capacitors have so many advantages, theses capacitors are not without defects. Depending on the dielectric material, the capacitance can vary dramatically with temperature, DC bias, and AC signal level. Because the capacitance can vary dramatically with temperature, when using the ceramic capacitor in the automotive applications, the circuit should be designed carefully because of the wide range ambient temperature. In addition, the piezoelectric nature of the dielectric material can transform vibration or mechanical shock into an AC noise voltage. In most cases, this noise tends to be in the microvolt level, but in extreme cases, mechanical forces can generate noise in the millivolt range.

Despite these disadvantages, because of a small footprint and low cost, ceramic capacitor is widely used in many applications. Designers must carefully evaluate the effects when using the ceramic capacitors.

2.2 Aluminum Electrolytic Capacitor

An aluminum electrolytic capacitor consists of a wound capacitor element, containing liquid electrolyte, that is connected to the terminals and sealed in a can. The element is comprised of an anode foil, paper separators saturated with electrolyte and a cathode foil. The foils are high-purity aluminum and are etched with billions of microscopic tunnels to increase the surface area in contact with the electrolyte. One of the important advantages of conventional aluminum-electrolytic capacitors is large capacitance. But these capacitors also have many disadvantages, such as relatively high leakage current, limited service lifetimes (thousands of hours), high ESR, and large capacitance variation. Also, these capacitors are not suitable to be used in high temperature applications because the electrolyte can dry out quickly.

The ESR of the aluminum electrolytic capacitor is high and varies a lot as the temperature changes. Therefore, more attention should be paid when using the aluminum electrolytic capacitor in automotive applications. The ESR of the aluminum electrolytic capacitors declines about 35% to 70% from 25ºC to the high temperature, but increases more than 10 times at the low temperature. Because the electrolyte becomes thick under low temperatures, the resistivity increases. Therefore, the ESR is greater under low temperature. Aside from temperature, the capacitance and the rating voltage are also affected by the ESR. Under the same rating voltage, the ESR of the aluminum electrolytic capacitor decreases as the capacitance increases. Under the same capacitance, the ESR of the aluminum electrolytic capacitor decreases when the voltage rating increases.

Because the ESR increases under low temperature, when using aluminum-electrolytic output capacitors in the linear regulator systems, instability can occur in low ambient temperature. If using aluminum electrolytic capacitors, TI recommends to select a low-ESR output capacitor to keep the linear regulator stable under all conditions.

2.3 Solid Tantalum Electrolytic Capacitor

A solid tantalum-electrolytic capacitor is another type of electrolytic capacitor, except the dielectric uses a metal tantalum. Compared with the aluminum electrolytic capacitor, the operating temperature range of solid tantalum-electrolytic capacitors is wider and can therefore be used with very high and low ambient temperature. Aside from this difference, the capacitance is more stable as the temperature changes. And, because the resistivity of the dielectric of the solid tantalum-electrolytic capacitors is less than that of aluminum electrolytic capacitors (1/10 or even less), the ESR of the solid tantalum-electrolytic capacitors is much smaller. Solid tantalum-electrolytic capacitors are generally more reliable than aluminum electrolytic capacitors because the dielectric of solid tantalum-electrolytic capacitor is more stable. In addition to these advantages, solid tantalum-electrolytic capacitors are less sensitive to the effects of temperature, bias, and vibration compared with ceramic capacitors. But the leakage current of solid tantalum-electrolytic capacitors is much larger than equal-value ceramic capacitors, rendering them unsuitable for some low-current applications. Another disadvantage of tantalum electrolytic capacitors is price; these types of capacitors are more expensive compared with the aluminum electrolytic capacitors and ceramic capacitors.

2.4 Capacitor Summary

Clearly, from the previous sections, the different capacitors have different advantages and disadvantages. Table 1 lists a summary of the critical parameters for the different types of capacitors.

Table 1. Comparison of Critical Parameters of Different Type Capacitors

Capacitor Type	Effective Series Resistance	Effective Series Inductance	Voltage Stability	Temperature Stability	Sensitivity to Vibration
Aluminum Electrolytic	Highest	Highest	Good	Lowest	Low
Solid Tantalum Electrolytic	Medium	Medium	Best	Good	Low
Multilayer Ceramic	Lowest	Lowest	Poor	Good	High

Figure 2 shows a graph of the ESR versus the temperature characteristics tested in the lab using 10-µF, 50-V ceramic, aluminum, and tantalum capacitors. The ESR of the aluminum electrolytic capacitor is around 100 Ω under –40°C and is around 6 Ω at room temperature. Therefore, when using the aluminum electrolytic capacitor, the ESR variation must be observed. Compared with the aluminum capacitor, the ESR of the tantalum capacitor and ceramic capacitor is smaller and more stable. The ESR of the tantalum capacitor in the whole temperature range is around 1 Ω, while the ESR of the ceramic capacitor is around 60 mΩ.

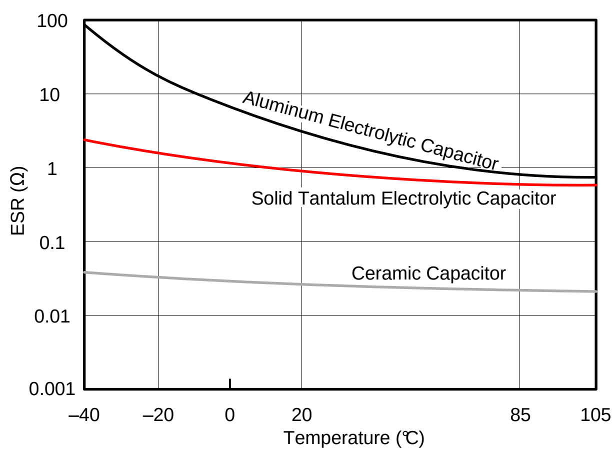
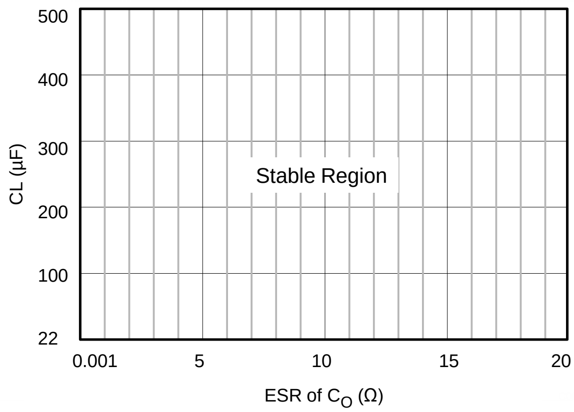


Figure 2. ESR Temperature Characteristics of Different Type Capacitors

3 TPS7B67xx-Q1 Output Capacitor Selection

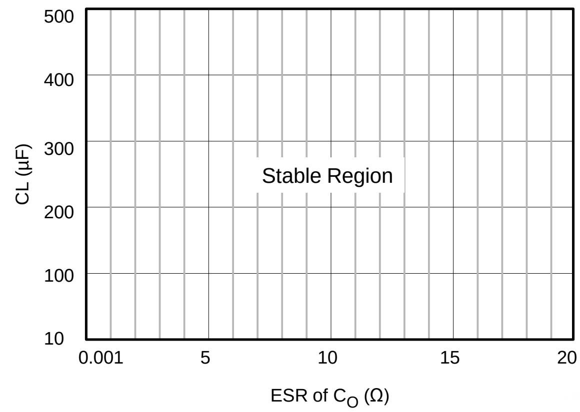
The TPS7B67xx-Q1 linear regulator has a wide output-capacitor range, which makes selecting the output capacitor easy. When the output voltage is larger than 2.5 V, a 10-µF to 500-µF capacitor with an ESR from 0.001 to 20 Ω can keep the output stable. When the output voltage is from 1.5 V to 2.5 V, the minimum, stable capacitor value should be greater than 22 µF. Figure 3 and Figure 4 show the stable region of the TPS7B67xx-Q1 linear regulator.

NOTE: TI does not recommended using a small bypass capacitor in parallel with the large ESR output capacitor because this configuration may result in oscillation of the linear regulator.



$V_O \leq 2.5$ V

Figure 3. TPS7B67xx-Q1 Stable Region of Output Capacitor



$V_O \geq 2.5$ V

Figure 4. TPS7B67xx-Q1 Stable Region of Output Capacitor

The TPS7B67xx-Q1 device has a large output capacitor and ESR range, therefore the output capacitor selection of the TPS7B67xx-Q1 device is flexible. For ceramic capacitors, because the ESR of ceramic capacitor is small (mΩ level), select a capacitor value within the stable region and the output will be stable. For a solid tantalum-electrolytic capacitor, the ESR is usually within several Ω, the ESR is still in the stable region, the output can be stable by selecting a capacitor value within the stable region. For an aluminum electrolytic capacitor, because the ESR is relatively large, additional attention should be paid to the ESR of the capacitor, especially under low-temperature conditions because the ESR of the aluminum electrolytic capacitor increases greatly under low temperature. From Figure 2, the ESR of the 10-µF, 50-V aluminum electrolytic capacitor is around 100 Ω under –40°C, and therefore it is not suitable for use as the TPS7B676xx-Q1 output capacitor. Actually in typical applications, a ceramic capacitor or solid tantalum-electrolytic capacitor is commonly used for the 10-µF level output capacitor. An aluminum electrolytic capacitor is typically used in applications requiring output capacitors greater than 100 µF. Because the ESR decreases as the capacitance increases, the TPS7B67xx-Q1 device can also support the large aluminum-electrolytic output capacitors. In this case, 220-µF, 50-V and 470-µF, 50-V aluminum-electrolytic capacitors are selected to perform the test. The ESR of the 220-µF, 50-V aluminum electrolytic capacitor under –40°C is 2.3 Ω. The ESR of the 220-µF, 50-V aluminum electrolytic capacitor under –40°C is 2.8 Ω. From these results, the ESR is in the stable region of the TPS7B67xx-Q1 device.

4 Test Waveforms

Performing a load-step test on the actual board under all output capacitor conditions is the most reliable way to determine if the board of an LDO has enough phase margin and gain margin. A resistor should be used at the output of the regulator that provides the load current. A MOSFET switch circuit is used to switch the load in a short time. The load should be stepped from no load to the rated load as fast as possible while the output is monitored for ringing or overshoot during the load step transient. Excessive ringing indicates low phase margin.

If the output capacitor meets the LDO requirements and is either still oscillating or drops too far during a transient, then increase the size of the input capacitor, and review the ESR. If the capacitor is a higher ESR capacitor, then use a lower ESR capacitor.

The TPS7B67xx-Q1 device is designed for automotive applications which typically have an ambient temperature range from –40°C to +125°C. Because the ESR of aluminum electrolytic capacitor under low temperature is large, a 220-µF, 50-V and 470-µF, 50-V aluminum-electrolytic capacitor was selected to test the TPS7B6701-Q1 board under –40°C. Figure 5 shows the schematic of the test circuit. Figure 6, Figure 7, Figure 8, and Figure 9 show the load transient waveform under low temperature. The TPS7B6701-Q1 device has good transient performance and can remain stable using the aluminum electrolytic capacitor under –40°C.

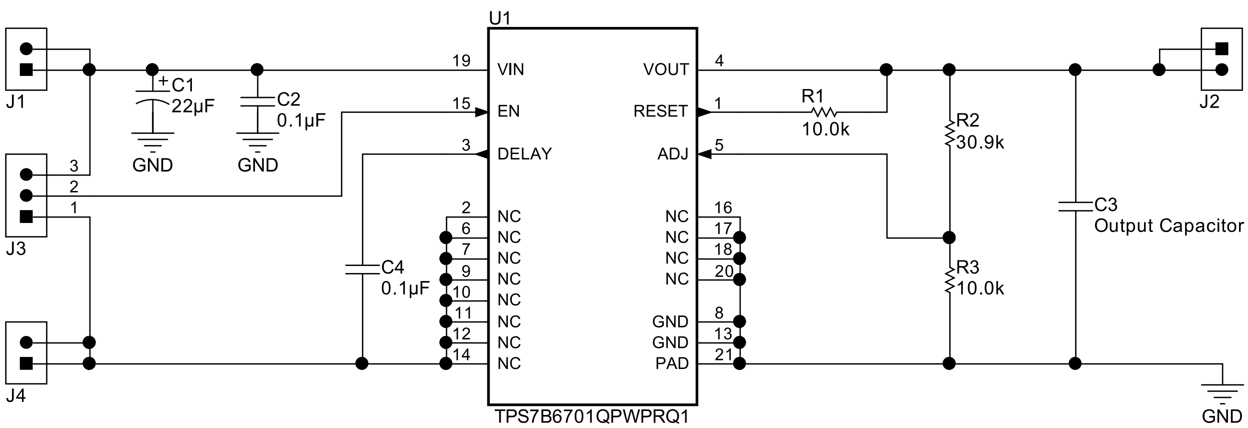
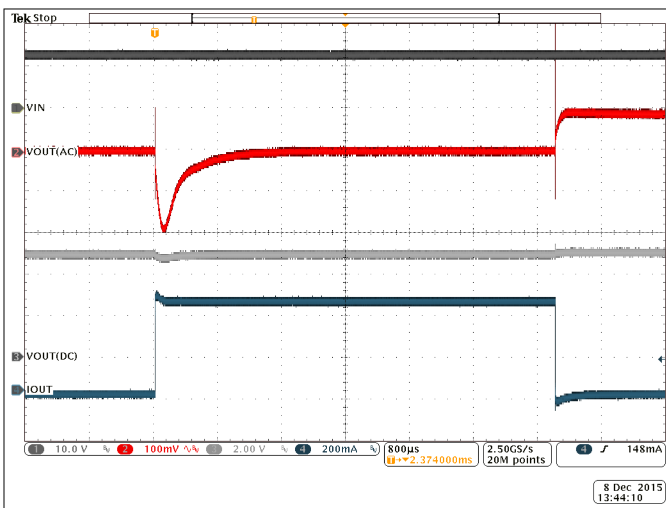
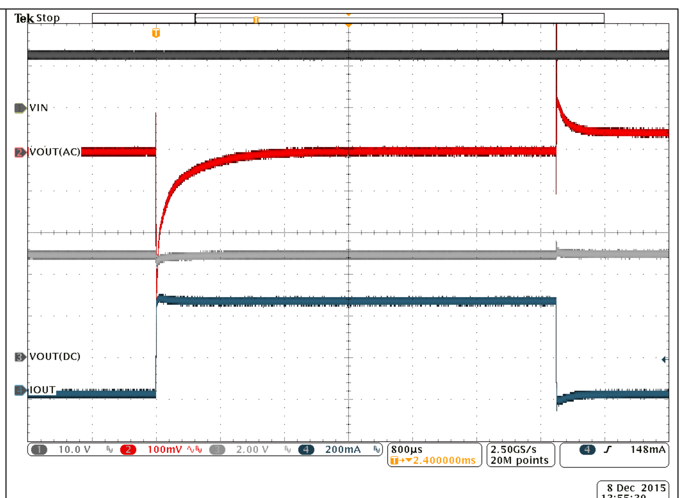


Figure 5. Test Circuit Schematic



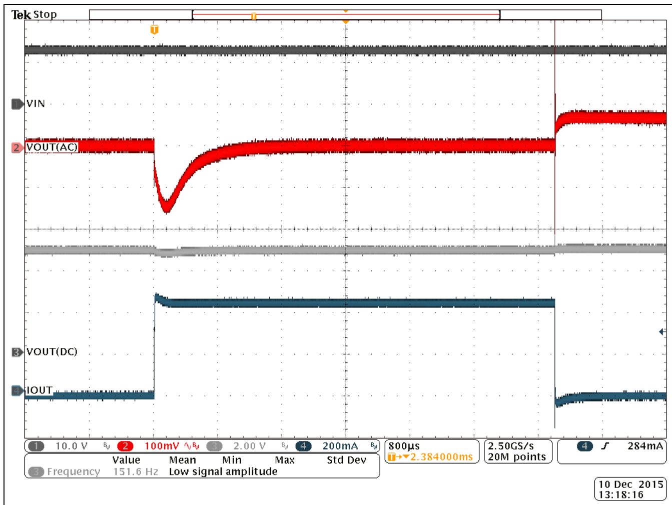
T_A = 25°C

Figure 6. Load Transient With 220-µF, 50-V Aluminum-Electrolytic Output Capacitor



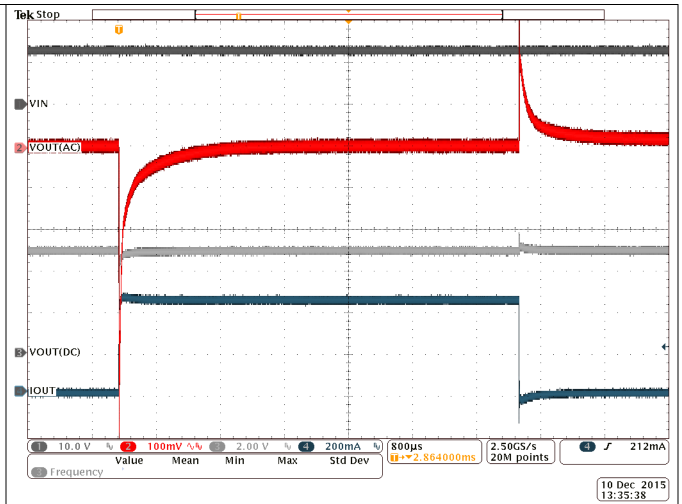
T_A = –40°C

Figure 7. Load Transient With 220-µF, 50-V Aluminum-Electrolytic Output Capacitor



T_A = 25°C

Figure 8. Load Transient With 470-µF, 50-V Aluminum-Electrolytic Output Capacitor



T_A = –40°C

Figure 9. Load Transient With 470-µF, 50-V Aluminum-Electrolytic Output Capacitor

5 References

For additional reference, see the following documents from TI:

- *Stability analysis of low-dropout linear regulators with a PMOS pass element* (SLYT194)
- *AN-1482 LDO Regulator Stability Using Ceramic Output Capacitors* (SNVA167)
- *Linear Regulators: Theory of Operation and Compensation* (SNVA020)
- *ESR, Stability, and the LDO Regulator* (SLVA115)
- *TPS7B67xx-Q1 450-mA High-Voltage Ultra-Low IQ Low-Dropout Regulator* (SLVSCB2)

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