Choosing and Using Bypass Capacitors

Introduction

Bypass capacitors are found in every working piece of electronic equipment. Systems, circuits, and individual chips require to be bypassed. Bypass capacitors are often chosen by convention rather than designed for the specific circuit. This application note aims to bring the design aspect back to this seemingly simple component. These are the main concepts: equivalent circuit, dielectrics, and types of available capacitors.

The next step is identifying the primary function and environment of the bypass capacitor. Circuits that exhibit large current spikes have different bypassing requirements than ones that solely operate at high frequencies. Several options are discussed, for example: scaling multiple bypass capacitors and the importance of board layout.

Finally, there are four application examples. These represent circuits with high and low currents and frequencies.

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1. Motivation

It is common to breadboard a circuit in an ideal configuration, but occasionally it does not work appropriately or does not work at all like the one shown in Figure 1. Noise can couple into the circuit from the power supply, internal IC circuitry, or nearby IC. Wires and board connections act like antennas and power supply levels change with current draw.

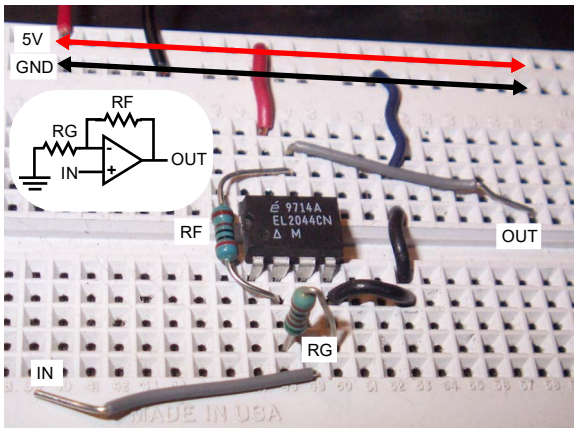


Figure 1. Breadboarded Non-Inverting Amplifier Configuration (AV = 2)

Figure 2 shows the result of the power supply pin on the oscilloscope.

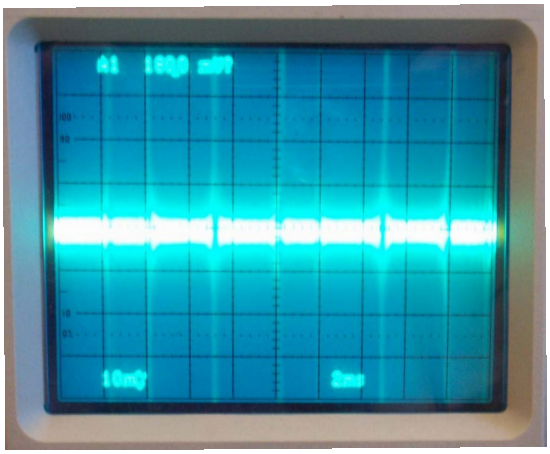


Figure 2. Oscilloscope View of DC Power Supply Pin on Non-Inverting Amplifier

High frequency noise shifts the DC level by approximately $10mV_{P-P}$. There are regular spikes in excess of 50mV more pronounced. Because power supplies are assumed to be stable (constant DC voltage), any perturbations couple directly into the circuit and get to the output depending on the PSRR.

The first line of defense against perturbations on the power supply is the bypass capacitor. A bypass capacitor eliminates voltage droops on the power supply by storing electric charge to be released when a voltage spike occurs. It provides this service at a wide range of frequencies by creating a low impedance path to ground for the power supply.

There are four questions to answer before grabbing the closest capacitor:

1. What is the size of the bypass capacitor required?
2. Where is the placement of the bypass capacitor for maximum effect?
3. What type of bypass capacitor work best/adequately in our circuit/system?

4. What type of package is required for the bypass capacitor? (depends on the size needed, the board area available, and type of capacitor chosen)

The simplest question to answer is #2, placement. A bypass capacitor must be placed nearest to the power supply pin of each chip. Any extra distance translates into additional series inductance, lowering the self-resonant frequency (useful bandwidth) of the bypass capacitor.

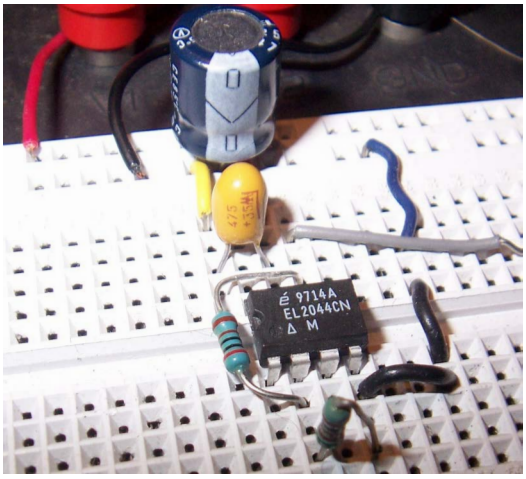


Figure 3. Breadboard Circuit of Non-Inverting Amplifier with Bypass Capacitors

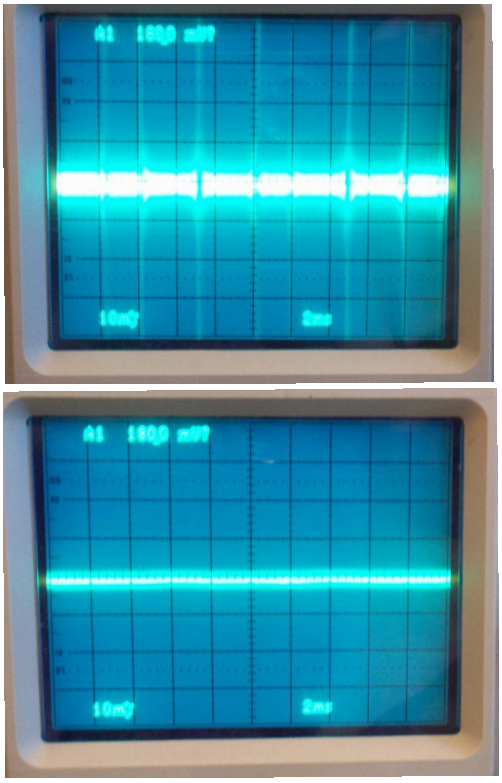


Figure 4. Output of Non-Inverting Amplifier shown in Figure 3 Without Bypassing (Top) And With Bypassing (Bottom).

Figure 4 shows the effect of the bypass capacitor on the output of the non-inverting amplifier.

The next topic discusses improvements in bypass capacitor placement and routing in the printed circuit board design.

The other three questions (about capacitor size, type, and package choice) are the core of this discussion. These topics are discussed in detail after the review of capacitor basics.

2. Capacitor Basics

The classic definition of a capacitor is two conductive plates separated by a dielectric material. As charge collects on the plates, an electric field builds across the dielectric. The amount of charge required to create a certain potential between the plates is referred to as capacitance and is measured in Farads. The capacitance can also be measured by the dimensions of the plates and quality of the dielectric shown in Figure 5, Equation 1. Capacitance increases as the area of the plates increases because more charge can be stored as the potential is created. The distance between the plates dictates the attraction between charges stored on them. As the distance increases, the interaction is decreased, and therefore so is the capacitance. This discussion relates the relationship shown in Figure 5, Equation 2.

The last of the basic equations involves current. By definition, current is the movement of charge shown in Figure 5, Equation 3. Therefore, there can only be movement of charge when the voltage (potential between the plates) is changing. If the voltage is constant, the charge forming it must be constant; with no flowing current.

In summary, the size of a capacitor has a direct effect on its ability to store charge. The second determining factor of capacitance is the quality of the dielectric.

2.1 Dielectrics

The dielectric is the material between the two conductors forming a capacitor. It has a high impedance and does not allow DC current to flow from one plate to the other. Different materials used as a dielectric have varying amounts of temperature stability, breakdown voltages and loss coefficients. The materials in Table 2 are accompanied by their dielectric constant (e), which is the coefficient that directly relates to the capacitance of a structure through Equation 1 in Figure 5.

Table 1. Examples of Dielectric Materials and Their Dielectric Constants

Dielectric Constant of Materials	
Air	1.00
Alsimag 196	5.70
Bakelite	4.90
Cellulose	3.70
Fiber	6.00
Formica	1.75
Glass	7.75
Mica	5.10
Mycalex	7.10
Paper	3.00
Plexiglass	2.80
Polyethylene	2.30
Polystyrene	2.60
Porcelain	5.57
Pyrex	4.00
Quartz	3.80
Steatite	5.80
Teflon	2.10

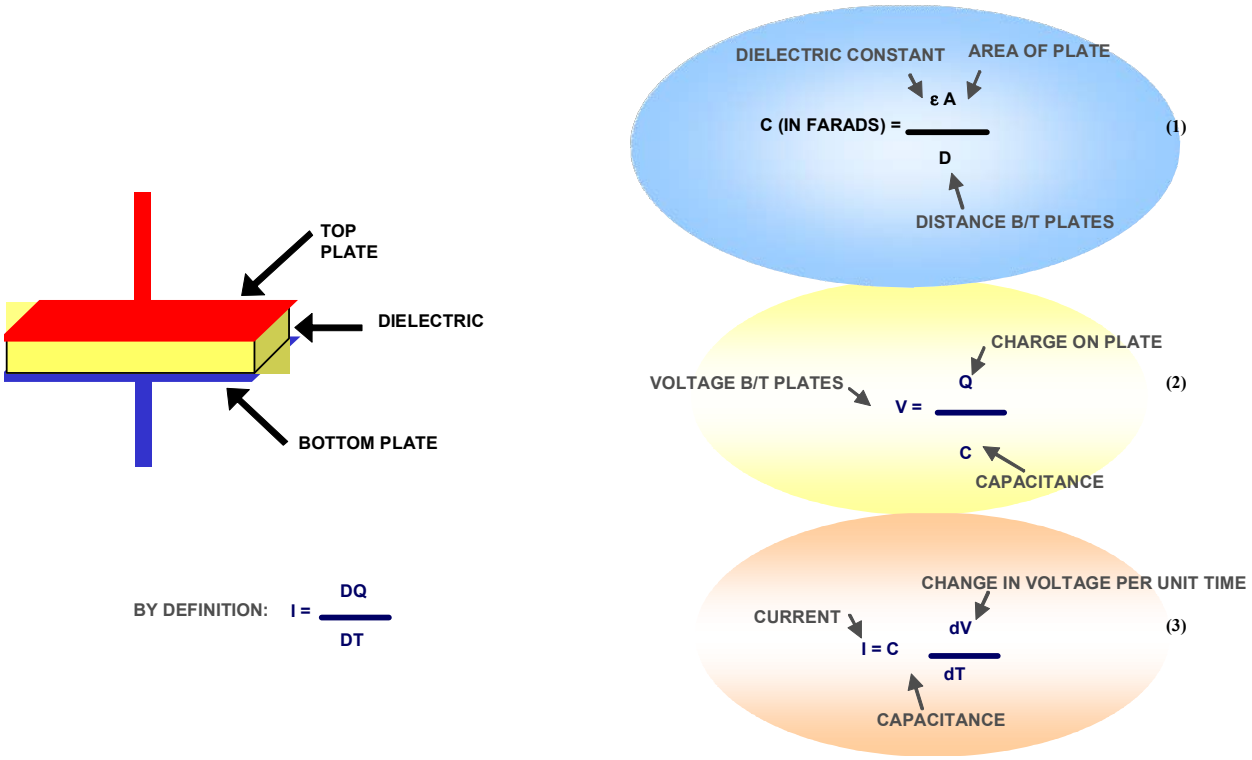
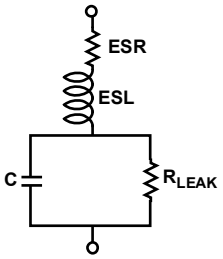


Figure 5. Capacitor Structure and Basic Equations

2.2 Equivalent Circuit Model

After the structure is understood, the next logical step is creating an equivalent circuit model to use in simulation. The equivalent circuit model is shown in Table 2. The main component, the capacitance, has a leakage resistance in parallel with it to represent any losses through the dielectric. In series with that RC pair is another resistive term in addition to an inductive term. These two values (ESR and ESL) represent the entire amount of DC and frequency dependent losses of the capacitive structure. The capacitor type and structure dictate the values of these parasitic components.

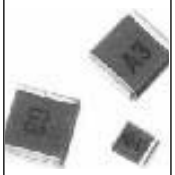
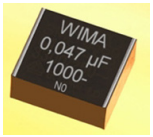
Table 2. Equivalent Circuit Model with Component Description

Abbreviation	Explanation	Source and Details
ESR	Equivalent Series Resistance	Wire and connections to the plate Produces heat
ESL	Equivalent Series Inductance	Depends on package type Surface mount better Smaller SMD better
RLEAK	Leakage Resistance	Type of dielectric
		

2.3 Common Types of Capacitors and Trade-offs

As described in the previous sections, the materials and structure of a capacitor dictate its attributes: parasitics, temperature stability, maximum voltage, linearity, cost, and size. A summary of the most popular capacitors available in surface mount packages is given in Table 3.

Table 3. Common Capacitor Specifications and Trade-offs

Type	Pic	Cap Range	ESR	Leakage	Voltage Rating	Temp Range	General Notes
Ceramic		pF to µF	Low	Medium	High	-55°C to +125°C	Multipurpose Cheap
Mica (silver mica)		pF to nF	Low 0.01Ω to 0.1Ω	Low	High	-55°C to +125°C	For RF Filters Expensive Very Stable
Plastic Film (polyethylene polystyrene)		few µFs	Medium	Medium	High	Varies	For Low Frequency Inexpensive
Tantalum		µFs	High 0.5Ω to 5.0Ω	Low	Lowest	-55°C to +125°C	Expensive Nonlinear (bad for audio)
OSCON		µFs	Low 0.01Ω to 0.5Ω	Low	Low	-55°C to +105°C	Best Quality Highest Price
Aluminum Electrolytic		High µFs	High 0.05Ω to 2.0Ω	Medium	Low	-	For Low to Med. Frequencies Inexpensive Hold Charge for Long Time - Not for Production Test

Ceramic capacitors are the most common capacitor type because they are inexpensive, offer a wide range of values, and provide solid performance. Tantalum, OSCON, and Aluminum Electrolytic capacitors are all polarized (specifically to be used as a bypass capacitor). Tantalum found their niche in low-voltage systems. Aluminum electrolytic capacitors are a common choice for low-to-medium frequency systems, but not switching circuits (they hold their charge too well and it does not work for the rapid cycling of production testing). OSCON is a special capacitor type developed to provide low parasitics, wide frequency range, and full temperature range (the best quality available for the highest price tag). These capacitors provide quality bypass for any circuit.

Mica and Plastic Film capacitors are included for completeness. Their primary use is in filter design instead of bypass.

Because ceramic capacitors are the most widely used bypass capacitors, look at the options available in purchasing. As expected, ceramic caps are available in a wide range of values and in a wide variety of packages. Within these parameters, there are further choices that determine the final price. An example is shown in Table 4. The bill of materials, the capacitors are labeled as X7R. The X and 7 set the widest temperature range. The final letter R reports the tolerance of that capacitor over the temperature range. In this case, there would only be a 15% change in capacitor versus temperature. A wider temperature range and tighter tolerance have higher price.

Table 4. Classification of Ceramic Capacitor Options

Ceramic (Eia Class Ii) Capacitor Code					
Letter Symbol	**Low Temp. Requirement**	**Number Symbol**	**High Temp. Requirement**	**Letter Symbol**	**Max. Δc Over Δt**
Z	+10°C	2	+45°C	A	±1.0%
				B	±1.5%
		4	+65°C	C	±2.2%
Y	-30°C			D	±3.3%
		5	+85°C	E	±4.7%
				F	±7.5%
X	-55°C	6	+105°C	P	±10.0%
				R	±15.0%
		7	+125°C	S	±22.0 -
				T	±22.0 -
				U	±22.0 -
				V	±22.0 -

2.4 Selecting the Package for the Bypass Capacitor

After the dielectric material, dielectric quality, temperature range, acceptable leakage, and voltage range have been met, the final choice involves package dimensions. Typically, the package size is chosen by what was used last time or what is big enough to solder by hand (if a prototype).

The equivalent circuit model changes with package geometry. The main issue is the equivalent series inductance (ESL). A capacitor structure is constant if the capacitance value is constant. If that same capacitor is available in a variety of packages, then the connections between the plates and the outer dimensions of the package must change. This appears as additional series resistance and series inductance. Smaller packages have lower series parasitics. Table 5 demonstrates this trend. The effective series inductance decreases monotonically as package size decreases. The 1206 has connections on the ends and the 0612 has connections on the longer edges. This simple change in orientation allows smaller inner package connections, reducing the ESL by 95%. In wide bandwidth circuits, the amount of series inductance sets an upper bound on the ability of the bypass circuit to provide a low impedance for the power supply pin.

Table 5. Surface Mount Packages and Their Equivalent Series Inductances

Package	ESL (pH)
0201	400
0402	550
0603	700
0805	800
1206	1250
0612	63

2.5 Sizing Bypass Capacitors

Bypass capacitors are usually sized by convention or typical values. For example, common values are 1µF and 0.1µF. The larger value handles the lower frequencies and high current issues and the smaller value handles higher frequencies. The requirement for multiple capacitors comes from the parasitics associated with real capacitors.

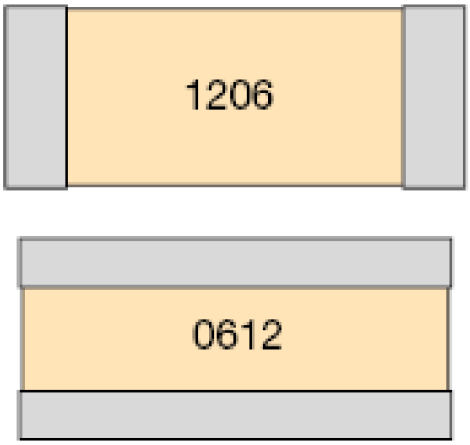


Figure 6. Example Surface Mount Packages in the 1206 Orientation (Top) and the 0612 Orientation (Bottom)

Figure 7 plots the impedance of a real capacitor. The axes are unlabeled so that the response can represent different capacitor values. The left half of the curve represents the traditional (and ideal) capacitor response; as frequency increases, the impedance of the capacitor decreases. This is desirable, because bypass capacitors provide a low impedance (effectively a short) to AC signals on the power line. The negative slope of the line is constant, but the lateral placement of the line is dependent on the size of the capacitor. For example, a larger capacitor shifts the left half of the curve lower in frequency (farther to the left).

Any inductance in the package of the capacitor cause a positive slope, as seen in the right half of the plot. In this region of frequencies, the inductance is canceling and then dominating the low impedance provided by the capacitor.

Because the amount of impedance is related to the size and construction of the bypass capacitor, the frequency response is related.

Check the datasheet to ensure the choice of bypass capacitor is available in a package that allows to provide the low impedance required for the frequencies present in the system. The ESLs quoted in Table 5 are in the range of hundreds of picoHenries. Their rising effect on impedance only emerges when system frequencies are 100MHz.

2.6 Bypassing a System with Wide Bandwidth

In some wide band systems, a single capacitor is not sufficient for bypassing. Multiple frequencies couple into the power supply lines and a bypass network must be used to provide a low impedance for a wider range of frequencies. Because the slopes, both negative and positive, of the impedance curves are physical limits, multiple capacitors are connected in parallel.

Select the packages of each of the capacitors precisely. A typical bill of materials can dictate that all passive components have the same geometry, all 0805 capacitors. The resulting impedance plot versus frequency for three parallel capacitors is plotted in Figure 9.

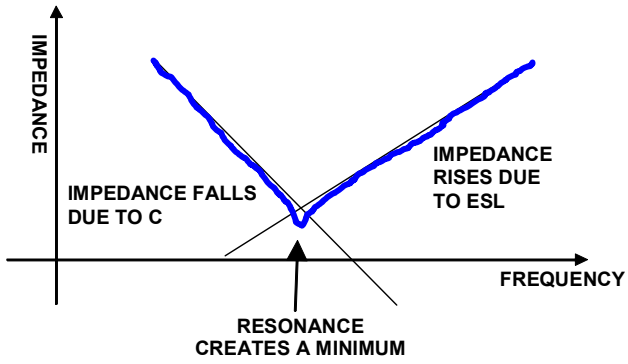


Figure 7. Impedance of a Capacitor (Non-Ideal)

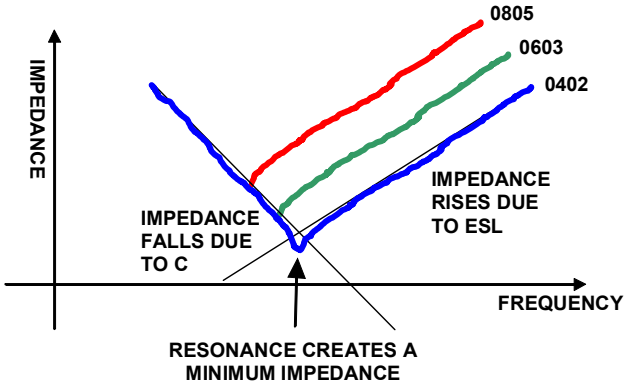


Figure 8. Impedance of a Capacitor (Non-Ideal) in Different Surface Mount Packages

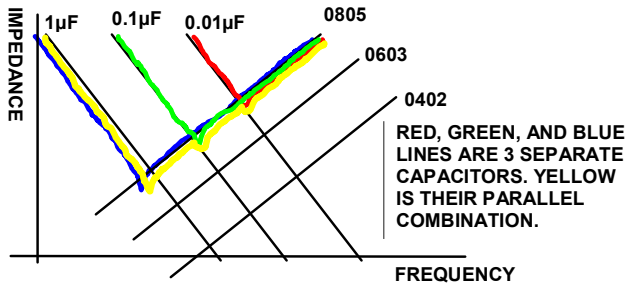


Figure 9. Impedance of Three Capacitors, the Same Surface Mount Packages

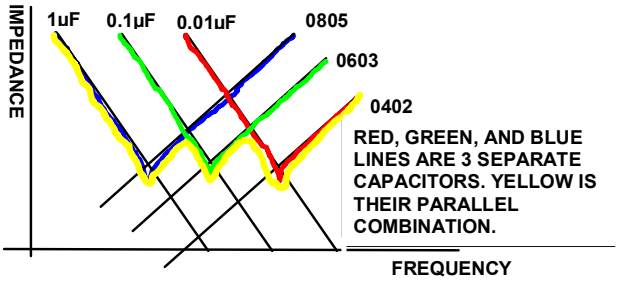


Figure 10. Impedance of Three Capacitors, Scaled Surface Mount Packages

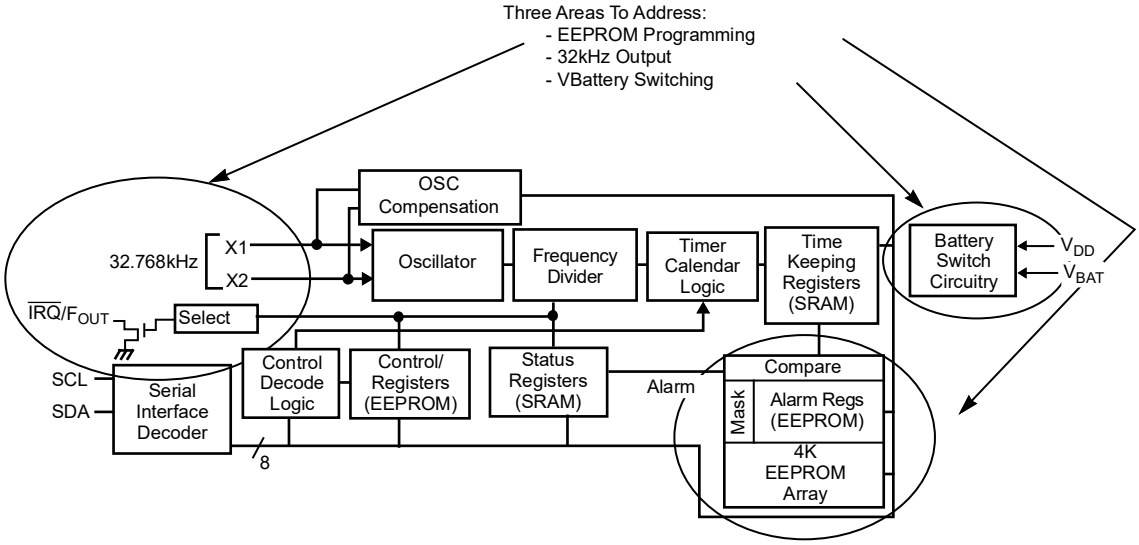


Figure 11. Block Diagram of Real-time Clock-Calendar with EEPROM Circuit

Because the same package was used for each of the capacitors, their high frequency responses are the same. Effectively, this negates the use of the smaller capacitors.

This level of detail demands strict attention to the layout of the bypass capacitors. Any additional trace length increase the impedance in the bypass path. Each trace contributes inductance per unit length; longer traces lower the useful frequency of the bypass path (shifting the curves of Figure 7 through Figure 10 to the left). Therefore, bypass capacitors must be placed the closest to the power supply pins. The opposite side of the capacitor requires a via to the ground plane or a wide ground trace to keep the impedance low.

2.7 Bypass Capacitor Application Examples

Each circuit and each system have specific demands that require to be addressed. The trade-offs involved in each particular instance are challenging. Therefore, four different application examples are presented. These examples are representative of low current/low frequency, low current/high frequency, high current/low frequency, and high current/high frequency systems. Table 6 shows the circuits.

Table 6. Application Examples for Bypass Consideration

	Low Frequency	High Frequency
Low Current	Real-time clock-calendar with EEPROM	Voltage reference
High Current	DC/DC converter	DSL amplifier

2.7.1 Example One (Low Current/Low Frequency): Real-Time Clock-Calendar with EEPROM

This system has three separate areas that require special bypass attention. This discussion assumes the use of an 8 Ld SOIC package.

The first area of concern is the EEPROM program array. To handle programming glitches, two capacitors must be placed in parallel at the supply pin, pin 8 of the SOIC. Use a small capacitor (0.01µF suggested) to handle digital switching transients. Use a large capacitor (1µF suggested) to compensate for current droops on the power supply. These two capacitors must be placed in parallel between the supply node and ground.

Crystal (X1) requires to be placed as close to the device as possible to eliminate high frequency coupling. If these traces are not minimized, additional bypass capacitors are required on the supply to remove any coupled signals.

This device allows for battery back-up. That feature is designed with a hand-off between line and battery power. Within this hand-off region, there is an overlap where both supplies are connected to the device. This supply overlap may cause switching transients. Adding a 0.1µF capacitor in parallel with the battery will minimize these transients.

2.7.2 Example Two (Low Current/High Frequency): Voltage Reference

The block diagram of our second example uses the ISL60002 to provide a voltage reference. Although voltage references are typically considered low frequency devices, they must be bypassed over the entire bandwidth of the system they are serving. Figure 12 shows the ISL60002 voltage reference regulating the supply of a high speed ADC.

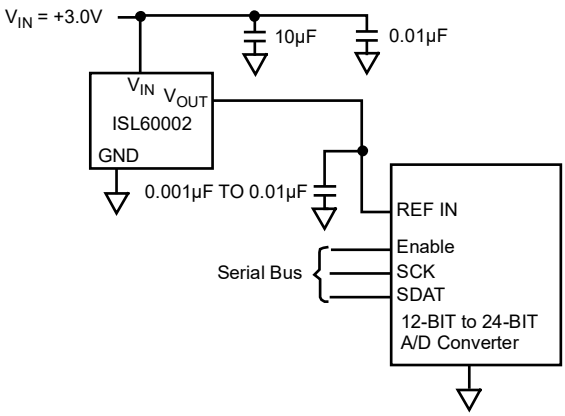


Figure 12. Voltage Regulator and ADC Block Diagram

In this example shown in Figure 12, the input to the voltage regulator is bypassed with the standard 2-capacitor fashion previously discussed in the sizing section. The output of the regulator is bypassed to provide a low impedance supply to the ADC.

If the ADC (or any other load) has a large input capacitance, add an RC to dissipate switching transient energy and reduce high-frequency ringing as shown in Figure 13.

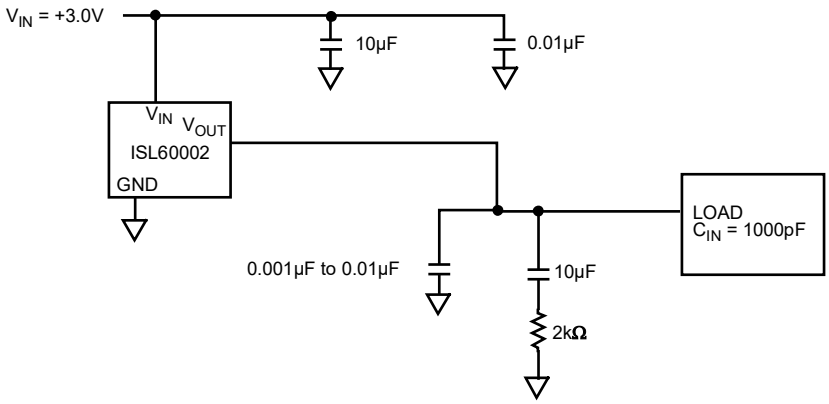


Figure 13. Voltage Regulator Bypassing with Large Capacitive Load

2.7.3 Example Three (High Current/Low Frequency): DC/DC Converter

The simplified block diagram of a DC/DC converter is shown in Figure 14. A pulse-width modulator controls switches to manipulate currents through large inductors to create the required output voltage.

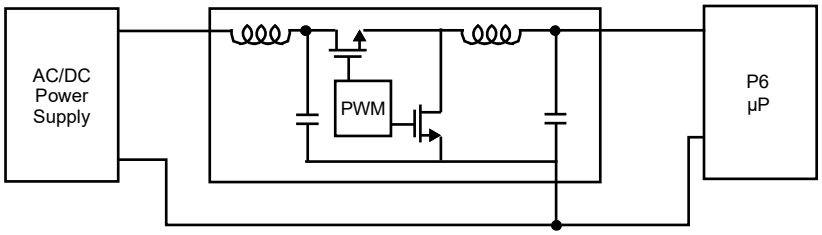


Figure 14. Simplified Block Diagram of A DC/DC Converter

The DC/DC converter circuit can be simplified when considering only one of the switching states shown in Figure 15.

Selecting the inductor is important. The circuit from Figure 15 is expanded to include the parasitics of the capacitor shown in Figure 16.

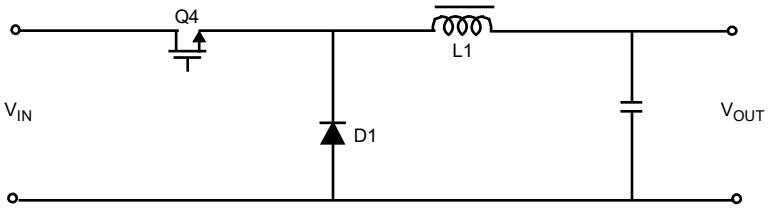


Figure 15. Active DC/DC Converter Circuitry in One Switch Configuration

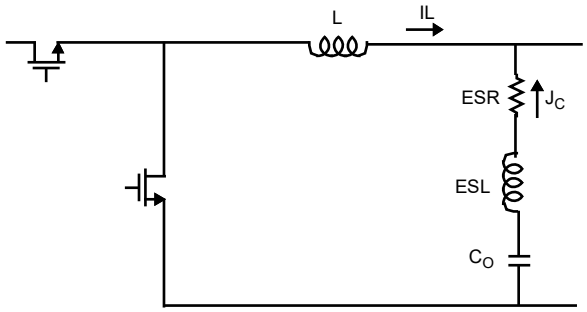


Figure 16. Simplified DC/DC Converter with Capacitor Parasitics

The effect of these parasitics is more apparent because of the large current through them. A summary is provided in Equation 1:

(EQ. 1) $$\Delta V_{OUT} = ESR \bullet I_{TRANSIENT} + ESL \bullet \frac{\Delta I}{\Delta T}$$

The output voltage exhibits ripple proportional to capacitor parasitic resistance (ESR) and parasitic inductance (ESL). The information in Table 3 gives the options to choose the best capacitor for the performance of their DC/DC converter.

This circuit requires bypassing the input and output as in the voltage regulator example. Layout is critical and multiple devices are commonly crowded around both supply terminals.

2.7.4 Example Four (High Current/High Frequency): DSL Amplifier

A DSL amplifier must handle the large currents required to drive communication lines at high speeds. Many of the same techniques reappear in this example. Bypass the amplifier as close to the supply pin(s) as possible. Any extra resistance (ESR) in the bypass path lowers the quality factor (Q). Any extra series inductance (ESL) lowers the self-resonant frequency of the bypass leg-possibly dipping into the bandwidth of the system.ESR and ESL are not only generated by the bypass capacitors, they appear in traces as well as through construction.

As shown in Example Two (Low Current/High Frequency): Voltage Reference, it is common to use at least two bypass capacitors in parallel. Two capacitors reside on the positive and negative supply. The smaller value capacitor appears in a smaller package and is placed closer to the device. Figure 17 presents the bypass capacitors C1 through C4 of the ISL1557.

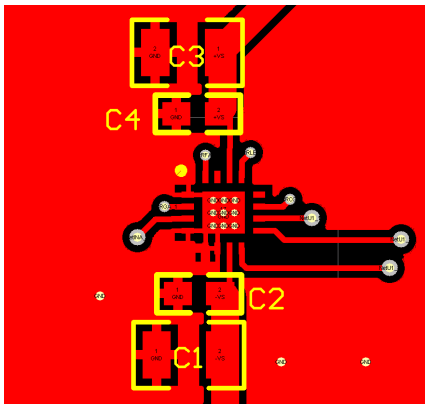


Figure 17. Layout of High Speed Amplifier Highlighting Placement of Bypass Capacitors

When the circuit operates at especially high frequencies, a third capacitor (smaller than the other two in size and value) must be added. The smallest capacitor must be placed closest to the supply pin to minimize parasitics. As the sizes of the capacitors increase, their respective distances from the supply pins can also increase.

There are designs with a series resistance to bypass capacitors to lower the quality factor (Q) of the bypass network. The effect is graphed in Figure 18 and Figure 19 using a simple, 2-capacitor bypass network.

Adding a series resistance lower the impedance compared to the frequency of the bypass network, but does not lower the overall impedance at any frequency. It is not recommended unless an especially flat frequency response is required.

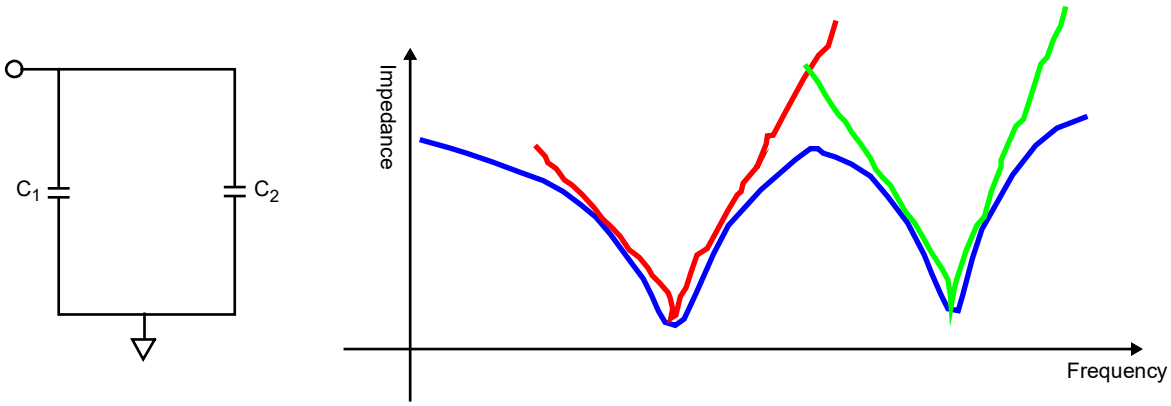


Figure 18. Frequency Response of Two Scaled Capacitors In Parallel (for Reference)

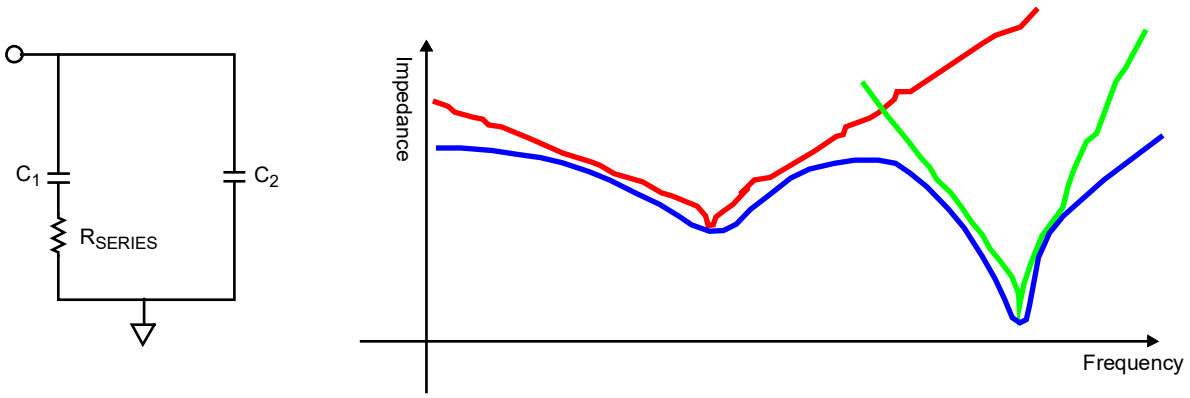


Figure 19. Frequency Response of Two Scaled Capacitors in Parallel, with One Capacitor De-Qed by Additional Series Resistance

3. Summary

An introduction and overview of bypass capacitor and bypass were discussed identifying two main issues: high currents and high frequencies. Select bypass capacitors to support the magnitude and edge rate of the expected transients while minimizing parasitic impedance. Many new specialized products are available for this very function (OSCON or X2Y). The most common solutions use multi layer ceramic chips caps.

No matter the capacitor chosen, layout is critical for quality bypassing. Bypass capacitors must be placed as close to the pins on the IC as possible to minimize additional ESR and ESL.

The specifics of the application examples provide insight into practical situations. One last resource is provided in Table 7 organizing other common circuits into the current/frequency matrix. Use this guide to identify major issues and confidently design better bypass networks.

Table 7. Other Application Circuits with Similar Current and Frequency Issues

	Low Frequency	High Frequency
Low Current	Precision amp Light sensors Real-time Clock/calendar with EEPROM	High-speed amplifier RF amplifiers High speed DAC/ADC
High Current	Sample and hold DC restore Amplifier DC/DC converter	Switching regulator RF amplifiers Precision DAC/ADC DSL drivers/receivers High-speed digital clock

4. Revision History

Revision	Date	Description
2.00	Nov 25, 2026	▪ Applied latest template ▪ Added Revision History section
1.00	Oct 10, 2011	Initial release

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Corporate Headquarters

TOYOSU FORESIA, 3-2-24 Toyosu,
Koto-ku, Tokyo 135-0061, Japan
www.renesas.com

Contact Information

For further information on a product, technology, the most up-to-date version of a document, or your nearest sales office, please visit www.renesas.com/contact-us/.

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