

Understanding Power Impedance Supply for Optimum Decoupling

Introduction

Noise in power supplies is not only caused by the power supply itself, but also the load's interaction with the power supply (i.e. dynamic loads, switching, etc.). To lower load induced noise, most uninitiated designers use the biggest, lowest impedance capacitor that can be found, thinking that this will absorb the dynamic load current. This method is often hit and miss, and can even cause the power supply to oscillate and make the situation worse.

A method will be presented that will ensure optimum decoupling of the power supply from the load. Only simple measurements of the power supply's output impedance and the decoupling capacitor impedance characteristics are needed for a complete understanding of the process.

The methods presented will work for all types of constant voltage power supplies; switching or linear, discrete or monolithic, and at any power level.

Power Supply Characteristics

Figure 1 shows a basic block diagram of a power supply (switching or linear). The output is sensed and compared to the reference. The difference voltage (error voltage) is amplified by the feedback amplifier and applied to the modulator such that at DC there is a -180° phase shift throughout the system (negative feedback) and the load voltage variation is corrected. This type of feedback electronically lowers the output impedance of the regulator, resulting in much better load regulation than the system would have with no feedback.

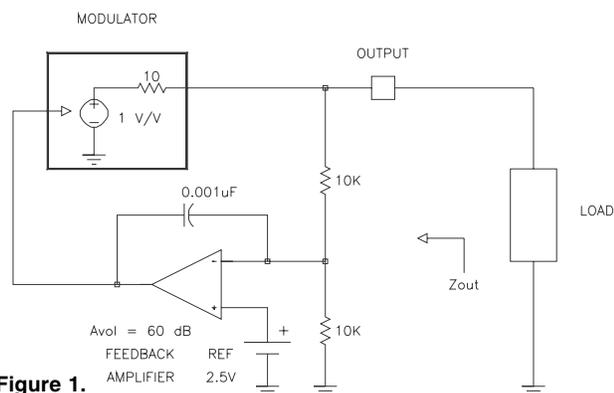


Figure 1. The circuit used to model the output impedance of a constant voltage power supply. The modulator can be either a linear regulator or a linearized switching regulator subcircuit.

The basic power supply is often thought of as having a low output impedance (good load regulation) for all frequencies. However, due to the power supply designer's need to roll off the feedback amplifier's gain with increasing frequency to insure a stable system, the output impedance will increase with frequency. This means that the output impedance is actually inductive (increasing impedance with frequency) for some range of frequencies.

Figure 1 shows how this increasing impedance with frequency characteristic results. The modulator in Figure 1 is modeled by a resistive source of 10 ohms (real power supplies may

have values from hundreds of milliohms to hundreds of ohms). The error amplifier has been replaced by a 60 dB open loop gain op amp connected as an inverting integrator. The output impedance of the modulator Z_m is reduced by the loop gain of the error amplifier circuit by the following equation, where T is the overall loop gain:

$$Z_{out} = \frac{Z_m}{1 + T} \quad (1)$$

At DC the loop gain is the 60 dB open loop gain of the op amp minus the 6 dB loss of the 2:1 voltage sensing divider or 54 dB. The DC output impedance from equation 1 is calculated to be 10 ohms / 502 V/V = 19.9 milliohms. At high frequencies the loop gain is zero and the output impedance is 10/1+0 = 10 ohms. In between these frequencies, the output impedance is increasing from 35 Hz (due to the integrator pole) with a slope of +1, or a ten times increase in frequency will cause a ten times increase in output impedance. The output impedance of this regulator is plotted in Figure 2.

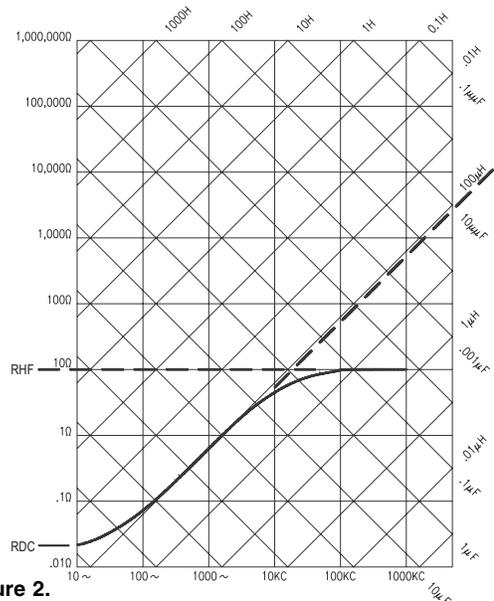


Figure 2. The output impedance of the circuit in Figure 1 plotted on reactance paper. The equivalent circuit values can be read directly from the plot.

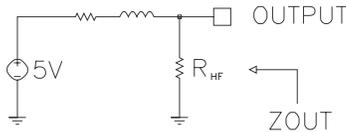
Not all power supply's open loop impedance can be modeled as a simple resistor though. The output also contains capacitors and inductors in the case of switching power supplies. But, because feedback theory forces designers to close the feedback loop at a single pole rate, the output impedance will always approximate the curve shown with small deviations at very low or very high frequencies.

It is not even necessary for the power supply user to have access to the power supply's schematic to determine the output impedance. Simple measurements at the power supply's output terminals can determine it (see sidebar "Determining Power Supply Output Impedance").

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Linear Equivalent Circuit for Output Impedance

A linear equivalent circuit for the output impedance of the regulator in Figure 1 is shown in Figure 3. The circuit values are easily derived if the output impedance is plotted on reactance paper. The values for R_{dc} , R_{hf} and L can be read directly from the graph. This equivalent circuit will suffice for almost all regulators. R_{dc} L



$R_{dc} = 0.02 \text{ Ohms}$
 $R_{hf} = 10 \text{ Ohms}$
 $L = 90 \text{ uH}$

Figure 3.
 This is the linear equivalent circuit of Figure 1.

Dynamic Load Interaction

The power supply will react to any load demand by presenting an impedance at the load's fundamental excitation frequency. For a DC load, the impedance is 20 milliohms. If a load that draws a 10 mA sine wave current at 2000 Hz (such as an oscillator) were attached, the output impedance would be 1.2 ohms and there would be a 12 mV sine wave on the output of the power supply. At any frequency over 20 kHz, the impedance looks like 10 ohms. Another commonly encountered load is the step load. The equivalent frequency of a step is $0.35 / \text{rise time}$. If a 100 mA step load with a rise time of 1 microsecond were impressed on the power supply, the power supply would present an impedance of 10 ohms (the equivalent frequency of the step is 350 kHz).

Decoupling the Power Supply for Improved Response

Once it is determined that the dynamic response of the power supply needs to be improved (and often times decoupling is just added for "safety"). The designer usually picks the largest, lowest impedance capacitor available and puts it on the power supply's output, believing that this will improve settling time or lower peak overshoot or both! This hit and miss procedure can make the situation even worse.

Figure 4 shows the result of adding a 47 μF capacitor to our example power supply. The transient response to a 100 mA, 1 μs rise time step before and after the capacitor addition is shown in Figure 4. The peak voltage has been reduced with the 47 μF capacitor added but there is a 2.5 kHz oscillation on the output. The 47 μF capacitor has brought the power supply to the brink of sustained oscillation. To see why, in Figure 5 the impedance of a 47 μF capacitor has been overlaid on the power supply output impedance. The two impedances cross at 2.5 kHz. The crossing is what causes the problem. The crossing is done at a rate of slope change of 2 (the up slope of the inductor and the down slope of the capacitor). Any rate

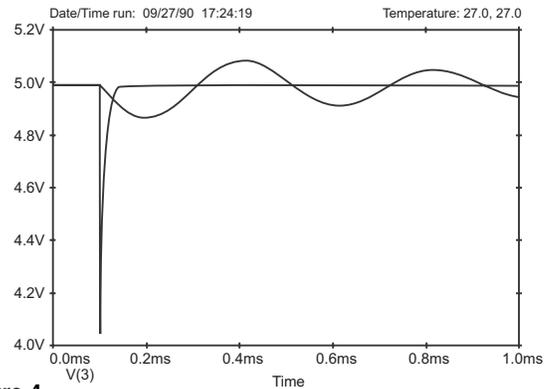


Figure 4.
 The transient response of the original circuit and the circuit with a 47 μF capacitor added. The 47 μF capacitor has brought the power supply to the brink of instability.

of change greater than 1 at a given frequency adds significant phase shift to the power supply's feedback, making it potentially unstable (and violates the fundamental rule that Bode developed for feedback stability; a loop closure at a greater than 1 slope rate of change is potentially unstable). At the 2.5 kHz cross over, the combined circuit forms an LC tank and the output impedance actually has a peak of 10 ohms at 2.5 kHz (combined curve, Figure 5).

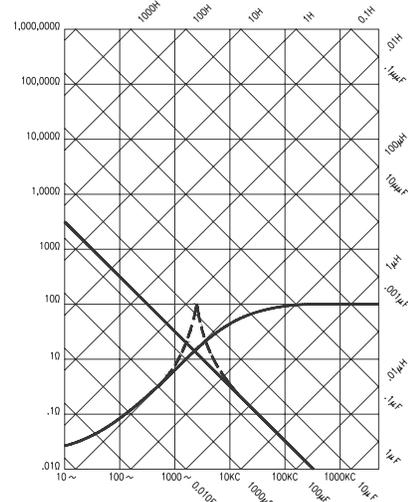


Figure 5.
 This shows the problem. The original circuit output impedance is overlaid with the impedance of the 47 μF capacitor. An impedance peak at 2.5 kHz reaches 10 ohms.

In real design, a perfect 47 μF capacitor cannot be found. All capacitors have at least two parasitic elements. They are the Equivalent Series Resistance (ESR) and the Equivalent Series Inductance (ESL) (see sidebar: "Know Your Capacitors"). If the 47 μF capacitor used was actually a subminiature aluminum electrolytic, the ESR might have been in the 2 to 5 ohm range. This would have "flattened" off the capacitor's impedance before crossing the output impedance curve and the severe impedance peak would not have occurred. If, however, the capacitor was a high quality tantalum, the impedance might have been in the 0.1 to 0.3 ohm range and the response and ringing would have been

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as described. This is why the hit and miss nature of power supply decoupling is often misunderstood. It depends more on the choice of capacitor type and construction than on the capacitor value.

Proper Power Supply Decoupling

The goal in decoupling is to reduce the high frequency impedance of the power supply without turning the power supply into a giant power oscillator. Once the maximum desired impedance at the frequency(s) desired is established from the known system load transients, the power supply can be examined to see if it meets the requirement by itself. Most well designed commercial power supplies will sufficiently provide low output impedance for 99% of all applications. However, if your supply/load combination needs improvement, the following design steps can be taken to improve the output impedance of the power supply:

1. Determine the power supply's output impedance curve.
2. Determine the maximum desired output impedance over the range of frequencies that your load will be exhibiting.
3. Determine which network in Figure 6 will give the desired output impedance.
4. Determine the component values for the damping network.
5. After the addition of the damping network, the output impedance should be verified to see if any resonant peaks are present.

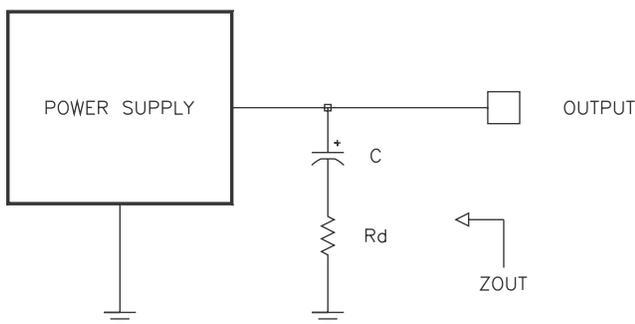


Figure 6A. Proper decoupling networks to be used to reduce the power supply's peak output impedance without introducing oscillation. This shows the single network.

In Figure 6A, a single capacitor / resistor has been added to the power supply output. The R_d might actually need to be added to the capacitor or it might be the capacitor's own ESR. This network is designed to provide a high frequency impedance of R_d to the load. The value for C is chosen as:

$$C = \frac{1}{2 \times \pi \times F \times R_d} \quad (2)$$

The break frequency F needs to be chosen somewhere below the intersection of the capacitor impedance and the output impedance of the power supply. To keep peaking to a

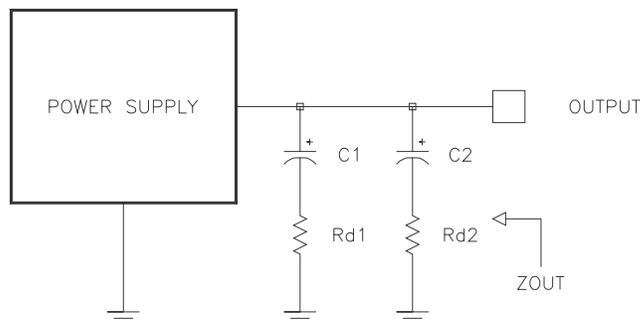


Figure 6B. This circuit can be used for the lowest high frequency output impedance.

minimum, F should be chosen to be anywhere from 0.1 to 0.7 of the no R_d crossing frequency. To have the resulting circuit be critically damped or better, the break frequency should be less than 0.4.

The circuit in Figure 6B is an extension of 6A. With the single RC circuit it may not be possible to realize the desired output impedance with real world components because of size or ESR limitations. The double circuit allows the power supply output impedance to be "flattened" at a low frequency by $C1/R_{d1}$, and $C2/R_{d2}$ can be chosen to be higher quality components that reduce the high frequency power supply impedance.

If any impedance in the circuit is less than a factor of 10 to the damping elements (RHF, for example), the two elements will interact as a parallel equivalent. This can throw the above damping equations off. The load also acts as a damping element and usually further damps the power supply.

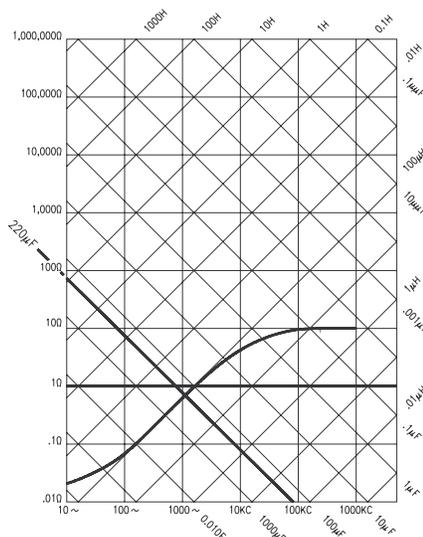


Figure 7. Proper Low Q damping network design. The 220 µF capacitors impedance is equal to 1 ohm at 0.4 times the crossing frequency.

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Putting Theory Into Practice

The following examples will clarify the design process:

Example 1:

It is desired to reduce our example power supply's output impedance for frequencies above 1000 Hz to below 1 ohm. Begin by plotting the power supply output impedance on reactance paper (Figure 7). Add the desired 1 ohm horizontal line to the graph. The crossing frequency is at 1700 Hz. A break frequency of 0.4 or 700 Hz is chosen. A standard capacitor that has a break frequency of 700 Hz with 1 ohm is 220 μ F. The damping network is now fully designed without even using a calculator!

The resulting circuit and transient response is shown in Figures 8 and 9. The restriction on the chosen capacitor is that its ESR adds to the damping resistance. A readily available 220 μ F aluminium electrolytic capacitor with an ESR of 0.2 ohms was chosen. This made the actual circuit value for R_d a 0.8 ohm film or composition type (not wirewound).

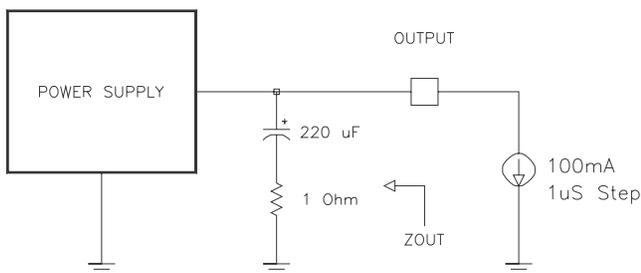


Figure 8.
The final damping network designed directly from Figure 7.

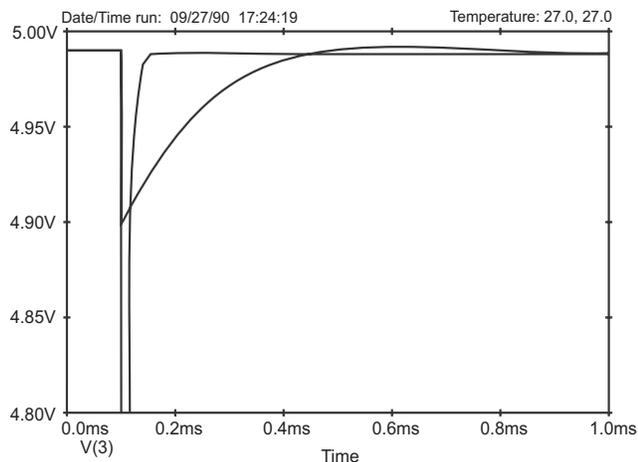


Figure 9.
This is the transient response of the circuit from Figure 8 superimposed on the original (Figure 3) circuit's response. Compare this response with Figure 4 (note that the Y axis scale factor is different from Figure 4).

Example 2:

If the single section damping network results in unrealistic capacitor and/or ESR values to keep impedance within the desired design goals, the circuit from Figure 6B can be used.

If we decide that the impedance should be as low as possible for frequencies from 10 kHz on up, 1 ohm starts to look pretty big. A second damping network can solve this problem, though. The design of the second damping network is similar to the first. The second damping capacitor's reactance should equal 1 ohm at a minimum of 2.5 times (1/0.4) the original crossing frequency. At 4250 Hz a 33 μ F capacitor has a reactance of 1.1 ohms. The second capacitor is usually chosen to be a tantalum or ceramic type because of the typically lower ESR and ESL of these types. The damping resistor for C2 is then just the ESR of the chosen capacitor. A readily available 33 μ F tantalum with an ESR of 0.2 ohms was chosen. The resulting circuit is shown in Figure 10.

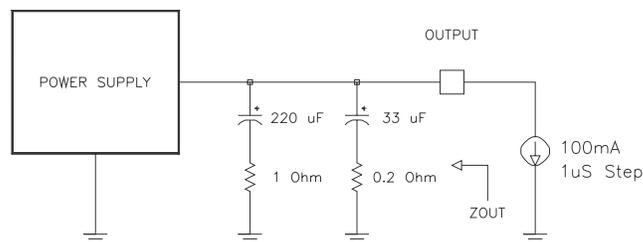


Figure 10.
High frequency damping added to the circuit of Figure 8.

It is important that the ESL of C1 is small enough at 4250 Hz so that C1's impedance is controlled by R_{d1} and not its ESL, or a secondary LC tank circuit will be formed. With high quality impedance specified capacitors, however, this usually isn't a problem.

The conclusion from these examples is that, while the peak overshoot can be substantially reduced with damping, the settling time to a 1 or 0.1% error band increases with damping. This is generally not as big a problem as peak values of overshoot, however. Large peak overshoots can cause false triggering of flip-flops and "glitches" in digital systems and can ring through the power supply rails of linear circuits. The settling time to 5 or 10% is nonexistent in the decoupled examples because the output never exceeds the error band.

Conclusion

Several simple "calculator-less" design criteria have been developed for the proper decoupling of power supplies. The techniques developed work for any power supply that can be characterized as having a non-constant output impedance vs. frequency.

The next time a fellow engineer adds a capacitor to a three terminal regulator or a kilowatt switcher you can look wise and all knowing by pointing out the error of his ways. Likewise expect several questions by your colleges on why you are "ruining" your capacitors by putting resistors in series with them. Then enlighten them!

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Know Your Capacitors

Capacitors are like all other electronic parts. They have parasitic components that cause them to deviate from their ideal characteristics. In power supply design, the most important parasitics are the capacitors' Equivalent Series Resistance (ESR) and Equivalent Series Inductance (ESL). Even these parasitic elements are not constant with time, temperature or frequency. At a frequency of 100 Hz, the ESR of the capacitor may approach ten times the 100 kHz value. Thus, when most power supply designers talk about ESR they really mean the maximum impedance of the capacitor when it is "flattened" out on the impedance curve. Power supply designers actually pick up capacitors and think that it is a 100 milliohm capacitor. The capacitance is secondary to them. ESR also changes from unit to unit and with temperature. The unit to unit variation can be 5:1 or greater for non-impedance specified types. It typically ranges 2:1 for units that have the impedance specified by the manufacturer. Temperature effects may vary the maximum impedance as much as 100:1 over a range of -55 to +105 °C with the change from 25 to -55°C accounting for most of the change (30:1).

ESL for most well designed capacitors does not effect their impedance until beyond 1MHz. However, this is not always the case. I have seen aluminum electrolytic types that have as much as 1 μ H of ESL. ESL is usually not specified and, in general, it is a construction or lead length issue resulting in 4:1 or less change with temperature or from unit to unit.

The capacitance specification is the easy part. It is relatively easy to buy ± 20 or $\pm 10\%$ parts off the shelf and the capacitance may change another $\pm 5\%$ over temperature.

Three type of capacitors are commonly used by power designers. They are aluminum electrolytic, tantalum and ceramic capacitors. Each has its own unique characteristics, advantages and disadvantages and each will be discussed below.

Aluminum Electrolytic: Capacitance values range from 0.1 μ F to 20,000 μ F and more. These types are used when large values of capacitance are required (i.e. 50-2000 μ F). Not all manufacturers specify the maximum impedance of their capacitors or how it changes over temperature. It is safe to assume, however, that an impedance specified type will have tighter manufacturing tolerances than a non-impedance specified type. In power work, always use a 105°C rated capacitor for extended reliability. The capacitance per unit volume is high and the capacitance x ESR product is good.

All specifications for the capacitor should be derated generously for maximum reliability.

Tantalum: Capacitance values range from 0.1 μ F to 680 μ F. These types are used when low values of impedance are required from a small sized capacitor. As with the aluminum electrolytic capacitors, not all vendors specify the maximum impedance. The spread of ESR from unit to unit and with temperature is about the same as with the aluminum electrolytic types; temperature stability is usually better. These types have very high capacitance per unit volume and excellent capacitance x ESR product. The ESL is usually lower than a comparable aluminum type due to the smaller size.

In general, tantalum capacitors provide excellent wide temperature range bypassing for power supplies. Again, for highest reliability, derate generously.

Ceramic: Ceramic capacitors are available from tens of picofarads to tens of microfarads. Several dielectrics are available with different temperature characteristics and stabilities. The most common values for power supply use are the 0.01 μ F to 1 μ F values. These capacitors have such typically low ESR that the ESL of the unit and its lead wire length dominate the impedance at high frequency. The term used with ceramics is "Self Resonant Frequency." This is the frequency at which the capacitor resonates as an LC tank with its own inductance. The self resonant frequency of a ceramic type is usually in the range of 2 to 50 MHz or more. Self resonant frequency is proportional to the capacitor's physical size, hence, it is lower for larger types. The capacitance per unit volume is low and the capacitance x ESR product is very high for ceramics. Derate the voltage by 40% or more for long life.

Ceramics are excellent choices for high frequency decoupling up to MHz.

Summary: Be wary and make your own measurements. This is where a very good LCR meter or low frequency network analyzer pays for itself. Be concerned with temperature, unit to unit, and long term changes in the capacitors' characteristics. If the power supply fails, the entire system shuts down. Buy from the highest quality vendors you can find.

Determining Power Supply Output Impedance

Power supply output impedance can be easily measured with the circuit shown in Figure B1. A function generator is used to introduce a small AC current into the output of the power supply. This current produces a voltage at the power supply output which is directly proportional to the output impedance at that frequency. By varying the frequency of the function generator in a 1-2-5 sequence over a range of 10 Hz to 1 MHz, an accurate plot of output impedance vs. frequency is made. To be sure of worst case effects, the plot should be repeated at the following extremes:

- Highest and lowest input line voltages
- Highest and lowest expected loads
- Highest and lowest expected operating temperature, at the two worst case combinations above.

By plotting the output impedance onto reactance paper, a linear equivalent circuit of the power supply can be made. The values for R_{DC} , R_{HF} and L can be read directly from the graph.

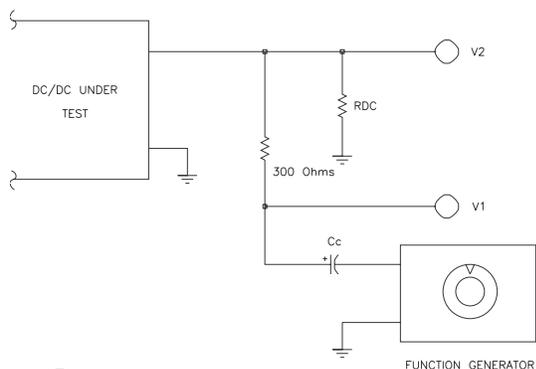


Figure B1.

Small Signal Output Impedance Test Circuit. Scale the 300 ohm Resistor as required so that $300 \text{ ohms} \gg R_{DC}$. A frequency sweep of 10 Hz to 1 MHz is easily obtained with most common lab function generators.