Making Measurements with the AP200 Frequency Response Analyzer

Introduction

Frequency response measurements are quite different from the usual measurements made on an oscilloscope. We normally use an oscilloscope to look at time-domain waveforms where we want to see an exact trace on the screen representing the electrical waveform in a circuit. Wideband oscilloscopes let us see all the frequency components at one time, with high-speed circuits requiring high-bandwidth oscilloscopes to see fast rise and fall times accurately.

Frequency response measurements also need to cover a wide range of frequencies, but the instrument measures *just one frequency at a time*. It must be able to measure this frequency accurately at very low levels, often much lower than other noise components in the system.

The frequency response analyzer outputs a sinusoidal test frequency, which sweeps over a very wide range, and measures the ratio of magnitudes of two test waveforms. Also, very importantly, it accurately measures the phase shift between the two signals.

Many industries benefit from making gain and phase measurements with a frequency response analyzer. These include the industries of power electronics and power supplies, audio, aerospace, chemical process and many others. In fact, any industry that uses an output test signal as part of a closed-loop system, or any industry that makes components that must be used over a wide range of frequencies.

The range of applications for a frequency response analyzer includes:

- Bode plots showing gain and phase of the loop of a feedback system with analog output. Includes power supplies, amplifiers, motor drives, and many other systems.
- Transfer functions from input to output for amplifiers, filters, power supplies, and equalizers.
- Impedances of active systems including amplifiers, batteries, and power supplies.
- Impedances of passive devices such as capacitors, inductors and transformers.

Enabling Innovation

The AP200 Frequency Response Analyzer, from Ridley Engineering, works with the Tektronix open Windows™ oscilloscopes to provide all these functions. In this application note, we will focus on the needs of the power electronics applications where transfer function measurements are crucial for a stable and reliable product.

AP Instruments AP200 Frequency Response Analyzer

The AP Instruments Frequency Response Analyzer is a very specialized instrument with the following features:

- Operating frequency range from 0.01 Hz to 15 MHz
- Swept-sine oscillator output to drive circuit under test
- Dual receiver channels to measure gain ratio of signals and phase shift with dynamic range of 117 dB.
- High noise rejection with selectable bandwidth of the receiver channels
- Direct interface to a computer for post-processing of data
- Automatic multiple sweeps to capture system variations with time, temperature, and component changes
- Automatic frequency-dependent variable source output to optimize loop measurements
- Software for processing and presentation of data

The oscillator outputs a test frequency, and the two receiver channels measure the ratio at that same frequency in the test circuit. The frequency is incremented in discrete steps from the start to the stop frequency, with a dwell time at each point to allow the circuit to stabilize.

Only a frequency response analyzer can do this job. A spectrum analyzer is similar in that it can measure a test channel with a very selective bandwidth, but it does not do gain and phase comparisons. Oscilloscopes by themselves do not have the necessary noise filters, dynamic range, tracking oscillator and measurement processing needed to perform the same function.

AP Instruments is now the dominant leader in the field, making the most practical, easy-to-use, and cost-effective analyzer on the market today. The Model 200 includes a parallel port control interface which works seamlessly with the Tektronix open Windows oscilloscopes. This allows you to make all of your frequency response measurements at the same time as monitoring critical circuit waveforms with the oscilloscope.

As we will see later in this application note, the process of analog loop injection and measurement and component impedance measurement is an essential part of the design process for many systems.

Transfer Function and Loop Gain Measurement

The most widely known use of a frequency response analyzer is for loop gain measurement. This is the most challenging application for the instrument, and some care must be applied in making these measurements.

The purpose of loop measurement is to verify the relative stability of a feedback control loop. The theory of this is beyond the scope of this application note, but is taught in all university courses on control theory. Criteria for stable systems were set up long ago by Bode and Nyquist, and these are still applied today in modern systems. Frequency response measurement of the loop is essential to generate the Nyquist or Bode plots.

The power electronics industry offers a severe technical challenge in making these measurements. A typical power supply loop gain will push the frequency response analyzer's specifications of dynamic range and noise rejection to the limit.

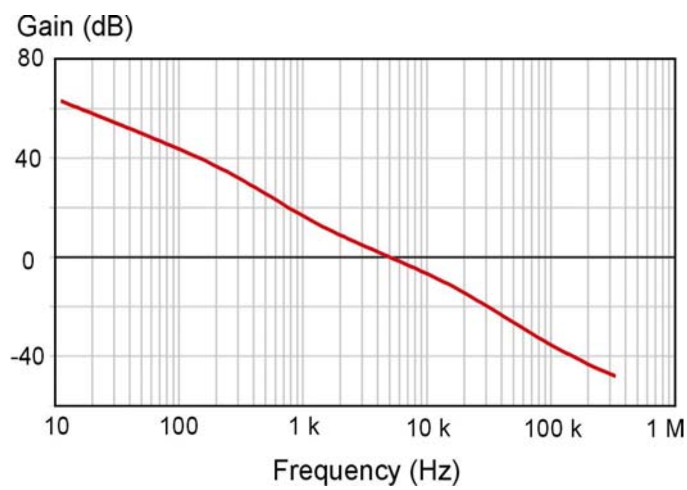


Figure 1. *Example Feedback Loop Gain*

First, we'll explain the difficulties involved in making these measurements. Figure 1 shows a typical power supply loop gain measured with a frequency response analyzer. At the low frequency end of a power supply loop measurement, the gain of the system will be very high– in excess of 60 dB, and sometimes as high as 80 dB. Consider the size of the signals needed to make this measurement. You must ensure that you are measuring "small-signal" with a small AC perturbation on top of the DC operating point. For this, the injected perturbation signal riding on the output will typically be 100 mV or less.

The input signal to the loop, for a 100 mV output, will be 0.1 mV for a gain of 60 dB, and 10 μV for a gain of 80 dB. It is common, however, to have several hundred mV of noise in the signals, as shown in Figure 2. It is impossible to measure the test signal in so much noise without a specialized instrument. This is where a frequency response analyzer provides its true value– extracting the test frequency only, with a very narrow bandwidth, so system noise does not interfere with the measurements.

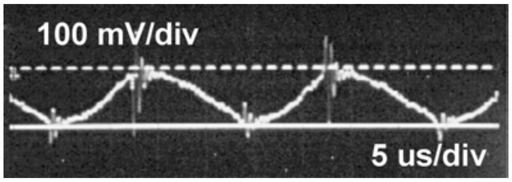


Figure 2. *Power waveform noise*

Loop Gain Test Setup

Power supplies are extremely high DC-gain systems. They use integrators to maximize the DC gain, and ensure that the output voltage DC regulation is tight. The power supply and control circuits cannot, therefore, be run with the loop open. It simply is not possible to hold the DC operating point steady with an open loop system.

Fortunately, there are established and documented techniques for measuring the open loop gain of a system while the loop is kept physically closed. The only invasion into the circuit is through the insertion of a test resistor. The technique is very accurate as it does indeed measure the true open loop gain of the system, not a gain modified by the injection technique itself.

This is shown in Figure 3. The only complication with this technique is that the signal must be isolated and injected differentially into the circuit across the resistor. The output signal from the network analyzer is coupled through an isolation transformer. This is preferable to an active device that may interact with the circuit.

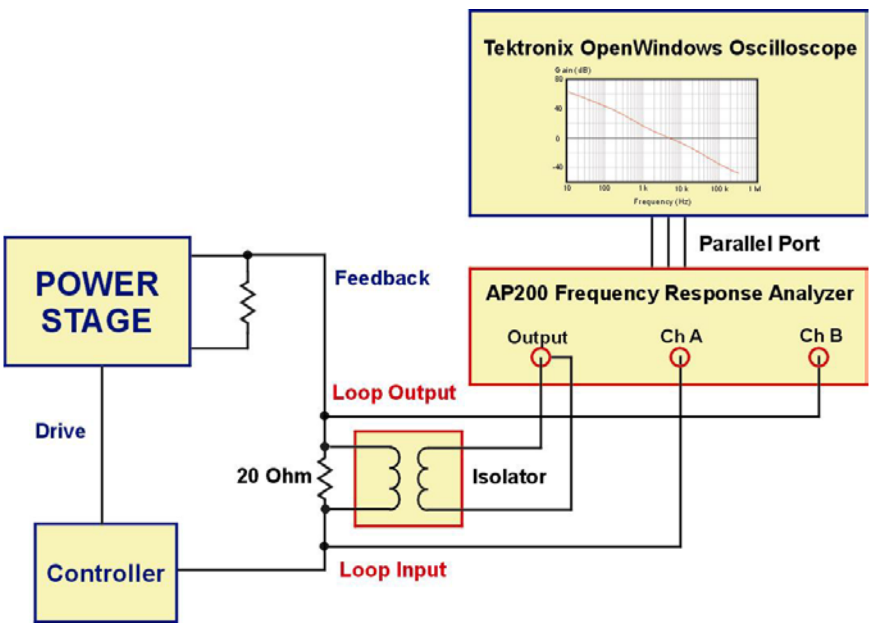


Figure 3. *Loop Measurement Setup*

It's a little unusual how this works– the signal size across the resistor is constant, determined by the output source of the analyzer. The vector sum of the injected signal and return signal are exactly equal to this injected signal. The power supply feedback system will adjust the signal sizes according to the gain of the loop. For example, if the gain of the system is 60 dB, and the injected signal is 100 mV, almost the entire injected signal appears across the output, with only 0.1 mV across the input.

At the crossover frequency, the injected signal is distributed equally between input and output signals. And, when the gain of the system is very low, (beyond the crossover frequency), most of the signal is applied to the loop input Only a small fraction is at the loop output.

In order not to disturb the operating point of the system, the injection resistor is kept small relative to other components in the circuit. Typically, a 20 or 50 ohm resistor is used.

During measurement, it is usually advisable to monitor critical waveforms of the control system to make sure that they remain in the small-signal region. An oscilloscope probe on the output of the error amplifier, and output of the power supply, is usually sufficient. As the gain of the loop changes, it is customary to adjust the size of the signal injection to keep the signals large enough to be measured, but small enough keep the system linear.

The injected signal size must be adjusted with frequency as the crossover of the loop is approached to make sure the system is not overdriven. It is useful to look at critical circuit waveforms, such as an error amplifier output, with the oscilloscope to verify that the perturbation is always kept in the small-signal range.

Example Loop Measurement

One of the reasons for making loop measurements on modern systems is that they do not always behave as predicted by theoretical models. We use measurements to find variations from theoretical predictions, and for cases where not all of the system parameters are well known

In this section, we use an example power supply measurement from industry.

A power supply that was ready to be released to production was measured with the AP Instruments Frequency Response Analyzer as described above. The loop was almost unstable, with only 35 degrees of phase margin at the selected nominal operating point, 50 degrees lower than predicted by modeling. The production release was delayed for a day to correct the problem.

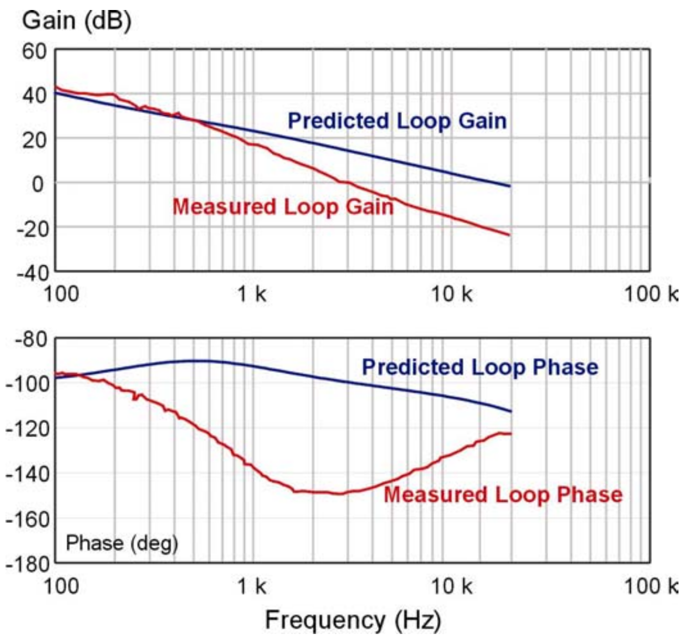


Figure 4. *Loop Measurement Example with Large Deviation from Initial Theory*

The theoretical model the engineer was using was fine, and all the values corresponded to the manufacturer's data for the passive components. And that's where the problem lay– the wrong value of ESR for the output capacitor was being used. It was correct according to the data sheets, which called out a maximum value of 7.5 ohms for a tantalum capacitor.

The real value of the ESR was only 0.25 ohms, which is a factor of 30 lower than the published maximum. This corresponded to a change in gain of 30 dB at a higher frequency. And, since we often cross a control loop over in the region where the output capacitors are resistive, the most crucial part of the loop gain often depends on this value.

A refinement to the model values confirmed the measured loop gain, and the need to add additional compensation components to the board. The cost of was only a few hours of engineering time, and the changes were incorporated in the final production board run the next day. The savings in potential product recall and re-engineering were substantial.

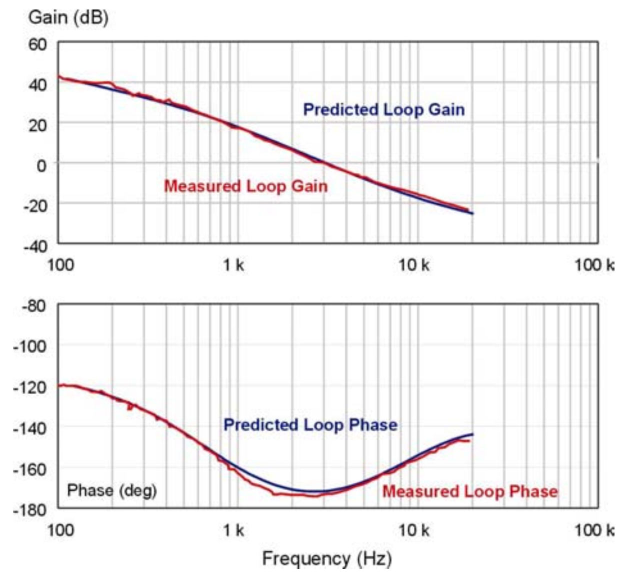


Figure 5. *Loop Measurement Example with Improved Modeling Values*

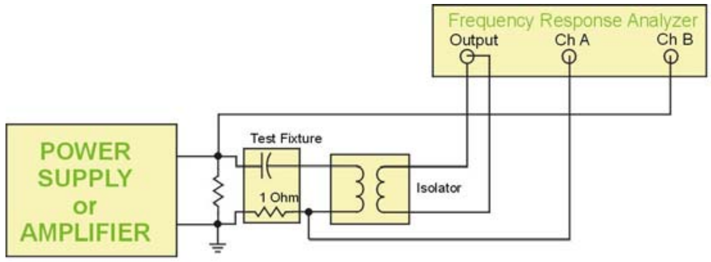
This example is more the norm than the exception. The loop measurement is often surprising when measuring the loop. That is one of the key reasons that this step remains a critical part of the power supply industry.

Other Transfer Function Measurements

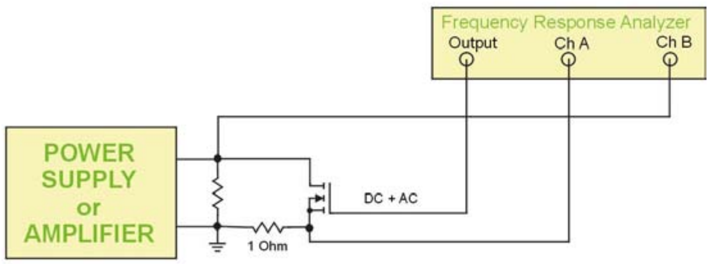
There are many more quantities that can be measured in a feedback system. For an audio amplifier, it is helpful to know the frequency response from input to output with the loop closed, and the output impedance.

For a power supply, input impedance, output impedance, and input-to-output attenuation are all important measures of system performance, which are properly characterized with frequency response measurement.

These quantities can all be measured effectively with a frequency response analyzer, as long as the systems can be perturbed sufficiently to provide adequate signals to measure. And that is not always an easy task, frequently requiring custom test circuits to inject into a system.



Low-Power Output Impedance Measurement (<100 W)



High-Power Output Impedance Measurement (>100 W)

Figure 6. *Circuits for Measuring Output Impedance of an Active System*

There is no standard, off-the-shelf equipment for doing these type of measurement. Test circuits are often custom-designed for the given application. Figure 6 shows two simple test circuits that can be used for measuring output impedance at different power levels.

Figure 7 shows a test circuit for injecting a test signal into the input bus of a power supply or power amplifier in order to make either input impedance or input-to-output transfer function measurements. This is the most invasive of all the frequency response measurements since it is necessary to break the main power bus.

This test brings up the problem of interfacing the measurement channels to high-power and high-voltage circuits. Frequency response analyzers have limitations of voltage that can be applied to their input terminals, and care must be taken to protect them. Battery-powered differential isolation probes are readily available to solve this problem. These provide complete isolation for the input channels up to 1000 VAC for both common and differential mode. The probes are used extensively by instrument makers, and can measure accurately to 20 MHz.

The differential probe in Figure 7 measures the perturbation on the input of the power supply system. The AP 200 analyzer allows for easy calibration of the instrument with different kinds of input probes and cables. This is a very important feature.

To make input-to-output transfer function measurements, the output of the power supply is connected to Channel B of the frequency response analyzer, as shown in Figure 7.

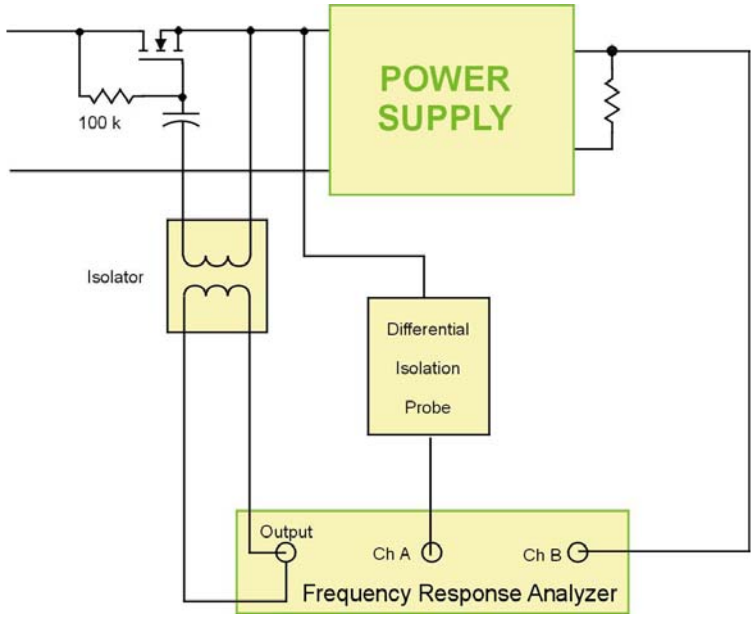


Figure 7. *Circuit for Measuring Input-to-Output Frequency Response or Input Impedance*

To measure input impedance of the power supply, Channel B is used to monitor the input current either with a current probe signal, current transformer, or resistor, depending on the type of circuit and power level.

The Future: Digitally Controlled Power Systems

Digital controllers are pervasive in many industries, using a microprocessor to control an analog system. This has been done for many years in production systems and slow-moving chemical systems. It is also now finding application in motor drives, and even high-frequency switching power supplies, systems that were classically controlled by analog feedback in the past.

This gives rise to the following questions: will we need to continue to make analog loop gain measurements in the future? Why can't the embedded processor measure its own loop?

These are good questions, and there are several important reasons why analog loop measurement will remain a part of our industry for many years to come.

It would take far too much circuitry and processing power to inject, filter, process, and measure the equivalent of an analog loop with an imbedded processor. The microprocessor would need to fill the entire function of the frequency response analyzer. This simply doesn't make sense. The hardware and software needed would burden the cost of the power system.

So why can't the processor measure the system, and work strictly in the digital control, or z-domain? The main reason for this is the very large separation of time constants in a switching power supply, and other analog systems. Digital processors can sample the system states very rapidly, but we still have a low pass filter in the power system– the fundamental building block of a PWM converter, or a chemical reaction, for example. Some of the control states can be moved rapidly from one microprocessor cycle to the next. But other analog process states barely move from one cycle to the next, even with maximum output from the control system.

This leads to discrete time poles of the system that cluster just inside the +1 point of the unit circle. It is extremely difficult to design such a system in the discrete time domain, and it is also numerically unstable to attempt to measure the poles with sufficient accuracy to predict the slow-moving transients of the power systems.

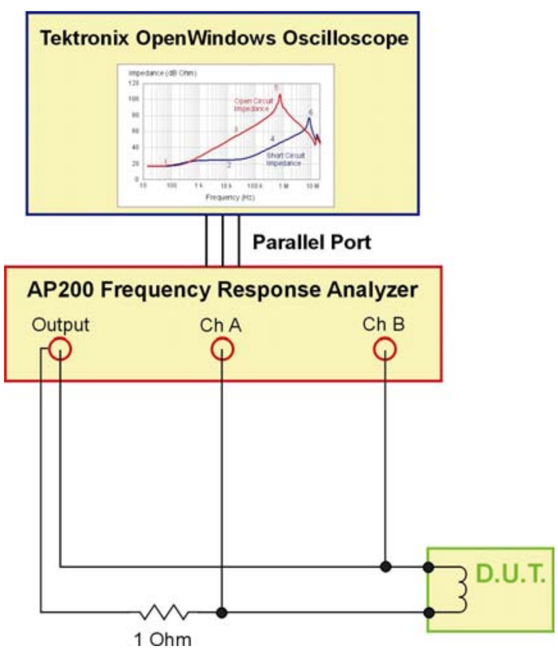
This effect has long been known. Computer-controlled systems have been with us for decades, yet they rely on analogy frequency response measurement in many cases to design a dependable system. This is especially true of switching power supplies where the system is very variable, often unpredictable, and always noisy.

Component Impedance Measurement

Once you purchase a frequency response analyzer, you will find that it has many uses beyond just transfer functions of systems. It is very valuable to perform a complete frequency response of the discrete energy-storage components used to build a feedback system, especially power components such as inductors, transformers, and capacitors.

Once you are familiar with the use of a frequency response analyzer, you will find it useful to measure all of the crucial components. This is important because they are frequently not well characterized by the manufacturers.

Manufacturers of parts do a satisfactory job of measuring the headline feature of a part they produce. If it is a 100 µF capacitor, it will be properly designed to measure 100 µF plus or minus the appropriate percentage. Capacitance is the one thing on a capacitor that does not require measurement.



The AP200 Analyzer is easily converted into an impedance-measuring device with sufficient range and accuracy for impedance measurements of power components.

High Impedance Measurement

There are two setups used to obtain accurate impedance measurements—one for high impedances, and one for low impedances. The high impedance setup is useful for inductors, transformers, and low-value capacitors.

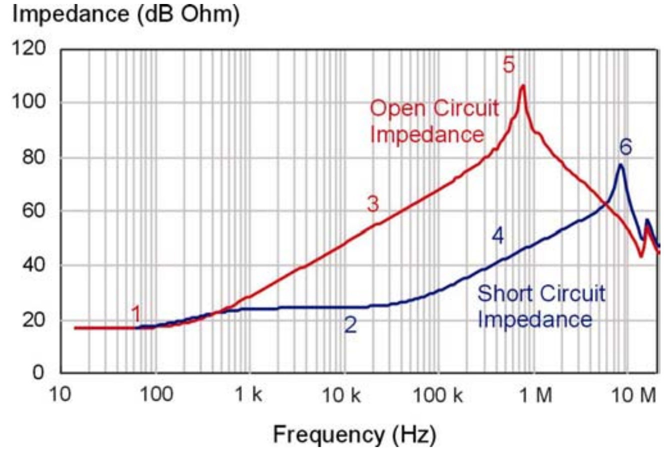


Figure 8. *Circuit for Measuring High Impedance Passive Devices such as Transformers, Inductors and Small Capacitors*

This setup is a very important circuit. It has the characteristic of being able to measure capacitances much lower than the input capacitance of the measurement channels, and values as low as 2 pF can be measured without any special calibration. This is very important for characterizing transformer and inductor winding capacitances and resonant frequencies.

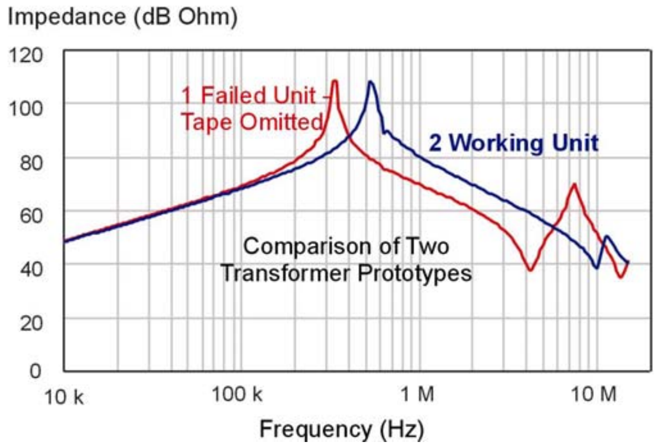


Figure 9. *Power Transformer Impedance Measurements*

Figure 9 shows example measurements performed with this setup. The first plot shows the open and short-circuit impedances of a power transformer. From this data, you can extract magnetizing inductance, leakage inductance, winding capacitance, resonant frequency, and Q.

The second plot shows how a layer of insulating tape omitted from a transformer led to a significant shift of the frequency response, and failure in the power supply.

In power supply design, collecting this data across the full range up to 15 MHz is an important part of the design documentation. It provides a complete picture of component performance over the full frequency range of operation. This provides a good basis for comparison of alternate source parts. Simple RLC numbers at a single frequency do not reveal changes and compromises in design.

This setup works well for impedances greater than the value of the sense resistor of Figure 8. The range can be shifted up or down by changing the sense resistor. For low impedances, however, it is preferable to switch to a low-impedance setup with proper Kelvin connections.

Low Impedance Measurement

The low-impedance measurement setup is shown in Figure 10. This setup cannot resolve high impedances, but can measure impedances as low as 1-mOhm up to above 100 kHz. The setup requires a wideband isolation transformer, and a Kelvin connection to the device under test. This is useful for large value, low-ESR capacitors commonly used in power supplies.

Figure 11 shows example measurements performed with this setup. These measurements are of several different capacitors, including multilayer ceramic electrolytic, and tantalum. The extremely low ESR of the multilayer ceramic can be clearly seen, and the effective range of each capacitor is shown. This impedance characterization step lets you optimize the addition of the right type and number of capacitors.

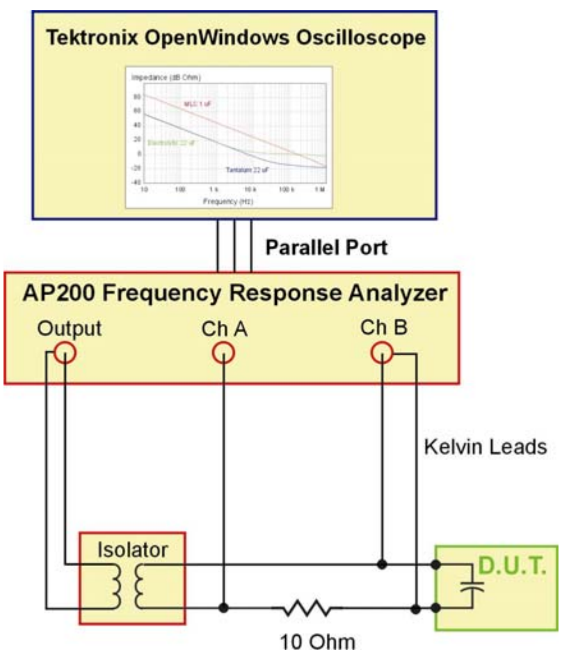


Figure 10. *Circuit for* Measuring *Low Impedance Passive Devices such as Capacitors*

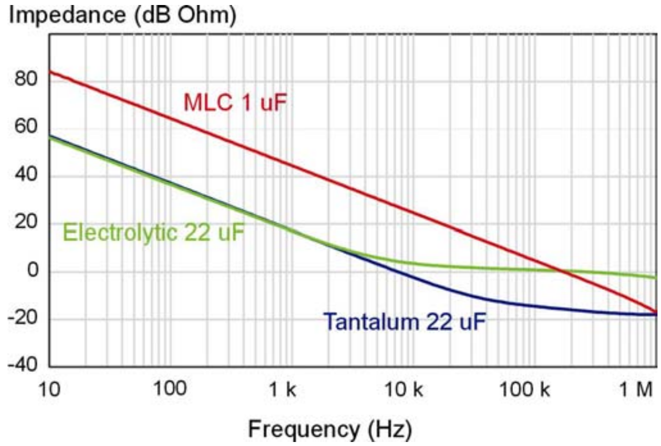


Figure 11. *Example of Impedance Measurements for Different Types of Capacitor*

Being able to accurately extract the ESR for the capacitors used is very important during product development. Manufacturers often specify ESR very loosely. It is often specified much higher that it measures. While this gives a better power performance than the data sheet promises, it is a big problem when relying on the ESR for loop compensation, or filter damping, as is often the case in power supply design. An example of this was shown earlier in this application note.

Summary

A frequency response analyzer is an essential tool for properly stabilizing feedback control loops. Paired with the Tektronix open Windows, the AP 200 from Ridley Engineering provides a complete lab solution for both waveform measurement, and transfer functions.

This application note furnished
Dr. Ray Ridley.