

Testing Loop Stability – PC Simulation or Real Measurement?

Background

Having designed the control loop within a power supply, motor drive or indeed almost any power electronics product, designers must establish that their target specifications for loop stability have been achieved.

Unlike ripple, noise, voltage deviation or recovery time when subjected to a transient load, control loop stability cannot be tested effectively with traditional test instruments such as a voltmeter or oscilloscope. So engineers faced with protracted testing on many separate instruments or costly specialist equipment often work on the assumption that circuit simulations will truly reflect the characteristics of the finished product. However, despite an apparently stable design based upon software simulation, the effect of pcb parasitic reactance, component tolerances in production or varying load conditions in normal operation can result in finished products that may not perform as expected, exhibiting instability or even failure.

Techniques used in modern instrumentation now provide engineers with cost effective test instruments that provide direct measurement of this critical design characteristic. Here we look at the subject of loop stability and economic solutions now available to simplify testing.

Control Theory

Control loop theory deals with the behavior of systems that are changing in time. While being a well established subject, we follow with a brief review of fundamental principals and for the purpose of illustration; we will consider one of the most common examples of this theory, the control loop within a power supply.

A regulated power supply is expected to provide its load with a stable output voltage and to do this, it must have the ability to adjust the characteristics of the system to maintain the desired output voltage under changing load conditions. This 'regulation' is achieved using a control circuit that feeds back a proportion of the power supply output for comparison with a known reference signal. This comparison produces an Error Signal that is then used to adjust gain within the power supply system so that the desired output is maintained. The following diagram illustrates this principle, which is true of almost any control loop.

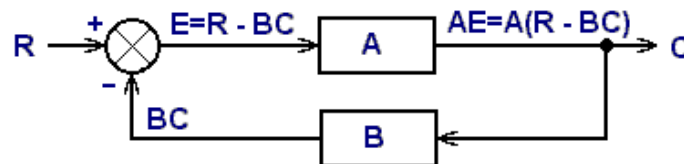


Figure 1.

- R = Reference – This is the input to the system
- A = Amplifier or Gain Stage – This is the system under control
- C = Controlled Variable – This is the desired output of the system
- B = Feedback stage – A signal that is proportional to the system output
- BC = Output from the feedback stage into the summing junction
- ⊗ = Summing Junction or Comparator – In this case, subtracting 'BC' from 'R'
- E = Error Signal – The output from the comparator

By considering the elements in this control loop, we can deduce a simple mathematical term that represents the effect that the loop will have on an input and use this to calculate the output C from any input R.

$$\begin{aligned}
 E &= R - BC \\
 C &= AE \\
 \therefore C &= A(R - BC) \\
 &= AR - ABC \\
 C(1 + AB) &= AR \\
 \therefore \frac{C}{R} &= \frac{A}{(1 + AB)}
 \end{aligned}$$

The term $\frac{A}{(1 + AB)}$ is referred to as the 'Transfer Function' of the system and the output of any control system (C) can be found by multiplying the input to the system (R) by the Transfer function, therefore:

$$C = \frac{A}{(1 + AB)} \times R$$

Loop Stability

Despite the apparent simplicity of control theory, analysis of loop stability under conditions that are changing in time becomes quite complex. Any closed loop feedback system can become unstable if, at any frequency, the phase delay round the loop is 360° or more while the loop gain is greater than 1 (0dB). At values close to 360° and 0dB the system can exhibit erratic behaviour even though it will not have sustainable oscillations. In order to preserve controlled behaviour of the closed loop system, two criteria are typically applied:

Gain margin: The loop gain should be -20dB or lower when the loop phase delay reaches 360°.

Phase margin: The phase delay round the loop should be less than 315° (45° margin) when the loop gain is greater than 0dB.

The most convenient way to view the frequency response or transfer function of a control loop is a bode plot, from which the gain and phase margin can be established. The following diagram shows a typical plot that may be seen on simulation software, with margin and crossover points shown.

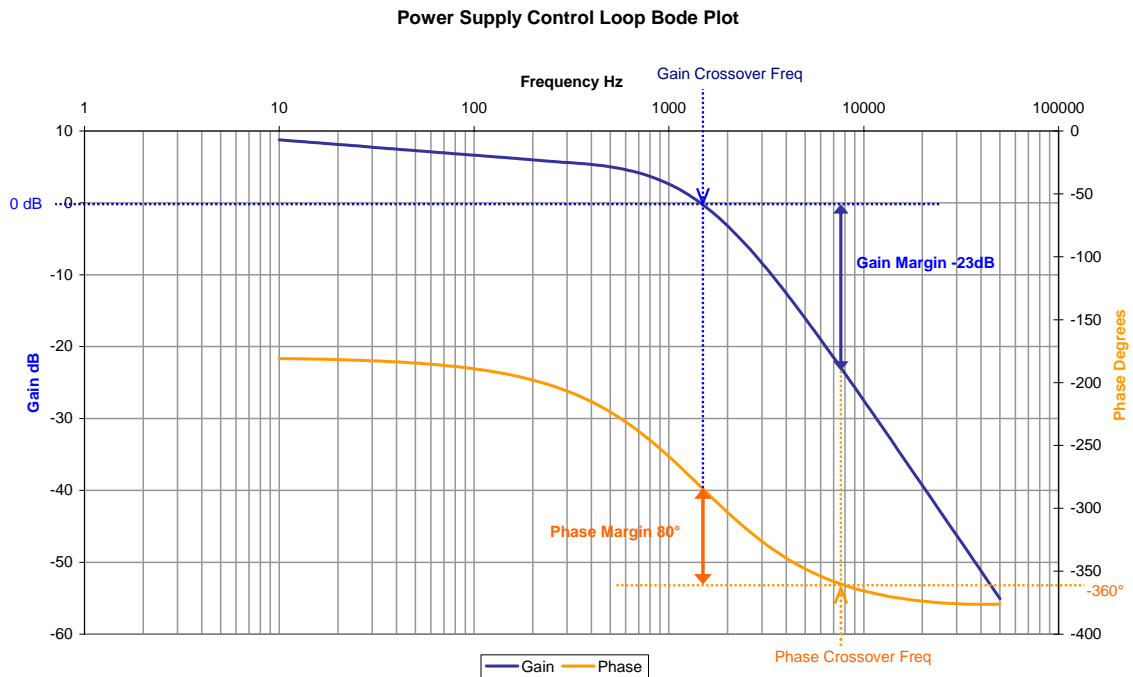


Figure 2.

Making Real Measurements

While software simulation provides a useful engineering tool, it can only offer an approximation of system response based on the information entered into the program and can therefore be an unreliable substitute for real measurements.

The first element required to permit real measurements in a closed loop environment is the injection of a disturbance signal. To achieve this, it is necessary to insert a small resistor (10Ω to 100Ω) into the loop at a suitable point where the small resistance has negligible effect (e.g. in series with the feedback resistors).

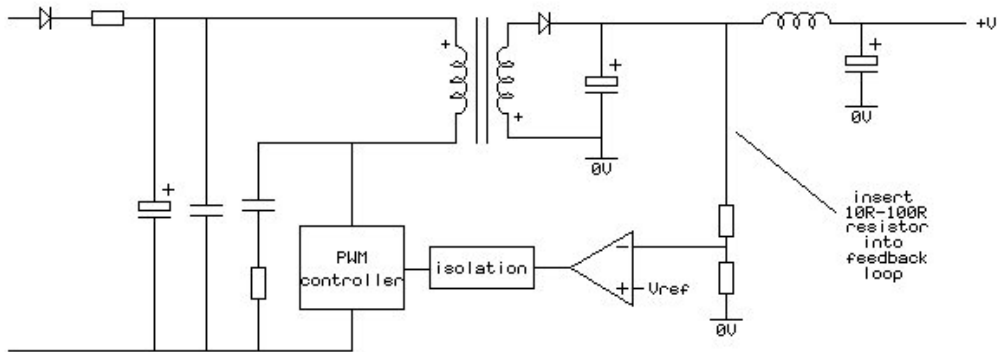


Figure 3. Simplified schematic of a switching power supply

Note: When laying out a new pcb it is worth tracking the resistor in permanently so that tests may easily be done at any time without disturbing the wiring.

In order to establish the Gain and Phase margin of the control loop, a sweep of discrete frequency disturbance signals should be applied across the inserted resistor via an isolation transformer that will ensure the control loop is not pulled down to earth. At each injected frequency point, the relative amplitude (in dB) and the relative phase (in degrees) must be measured either side of the inserted resistor. These values reflect the closed loop gain and loop delay at the respective test frequencies and are used to produce a frequency response plot of the loop from which loop stability can be established.

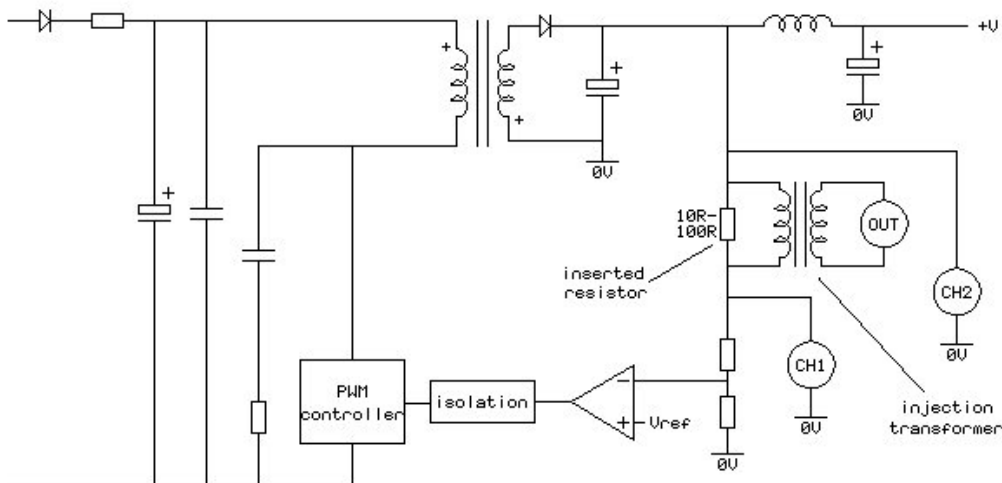


Figure 4. Simplified schematic of a switching power supply showing connections for loop stability measurements

Figure 5.

Example of an injection transformer being used to inject a disturbance signal into the control loop of an open frame switched mode power supply



To effectively measure the relative gain and phase of the injected signal, frequency components other than that of the injected frequency must be rejected and this is best achieved using a DFT (Discrete Fourier Transform) on the measured data from CH1 and CH2 as each selected frequency is injected.

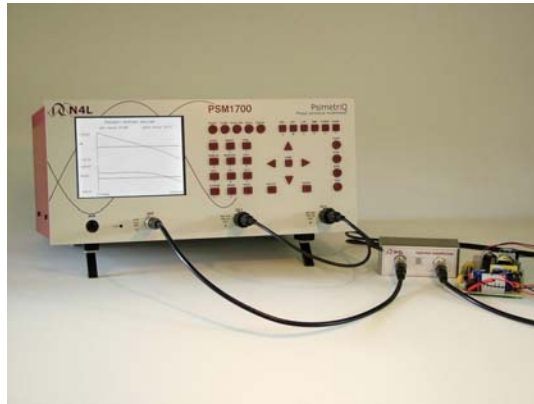


Figure 6.

Example test configuration with an SMPS being tested by a phase sensitive multimeter with two voltage sensing measurement channels and an inbuilt signal generator connected to the control loop via an injection transformer as shown in Figure 5.

By plotting the DFT processed measurement results from CH1 and CH2 directly into a graphic display during the frequency sweep, PC processing is not required to obtain a complete frequency response bode plot.

Figure 7.

Example of a power supply bode plot under LOW load conditions with gain and phase margin readings selected and a cursor at the gain crossover point.

Here it can be seen that despite good gain and phase margin values, system gain and crossover frequency are low, resulting in poor regulation and reduced stability with a rapid load change.

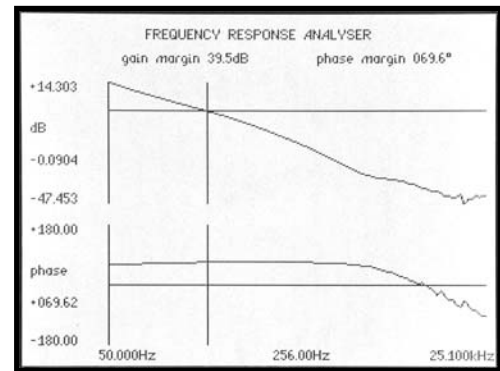
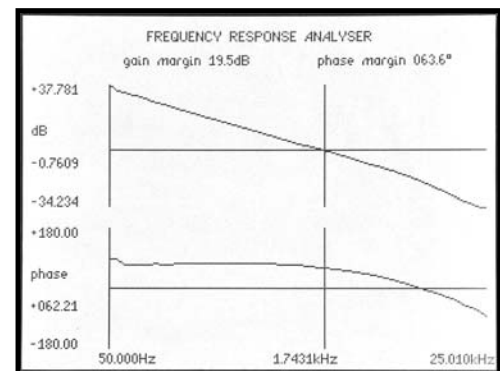


Figure 8.

Example of a power supply bode plot under FULL load conditions.

Here it can be seen that while the gain margin is lower than that under a low load condition, it is still adequate and there is much greater gain over a wide frequency range, which will result in superior regulation and greater stability with a rapid load change.



Design Considerations

The bode plots shown on Figure 7 and Figure 8 illustrate that in order to establish meaningful performance characteristics of a power supply, it is necessary to measure the transfer function over the range of load conditions under which the power supply will be expected to operate. Having established the transfer function under the chosen load conditions, design changes to achieve the best overall performance require consideration of 'pole' and 'zero' elements within the complete transfer function.

A 'pole' element is one that introduces attenuation (-20dB per decade) and negative phase shift while a 'zero' element is one that introduces gain (+20dB per decade) and positive phase shift. The complete transfer function is therefore the combination of pole and zero elements within the control loop. As almost any system exhibits attenuation at higher frequencies, there will usually be more poles than zeros.

If we consider the low load transfer function shown in Figure 7, it can be seen that the attenuation at frequencies up to the gain crossover frequency is quite consistent and in the order of 20dB per decade, suggesting a single dominant pole. We have not included a full schematic of the power supply in this article but for the purpose of illustrating a principal, we could consider this dominant pole to be associated with capacitance in the error amplifier stage of the control loop. Reducing the value of capacitance within this stage would increase the pole frequency and therefore also the gain, improving the low frequency regulation. The change in transfer function associated with this modification will of course influence the gain and phase under all load conditions, so it is necessary to repeat tests over the complete load range to ensure that gain and phase margins remain within target limits.

Conclusion

While PC simulation is a valuable tool at the early stage of a control loop design, an understanding of true control loop characteristics can only be achieved with real measurements on the completed design and modern instrumentation can now provide an accurate and economic solution to this need.