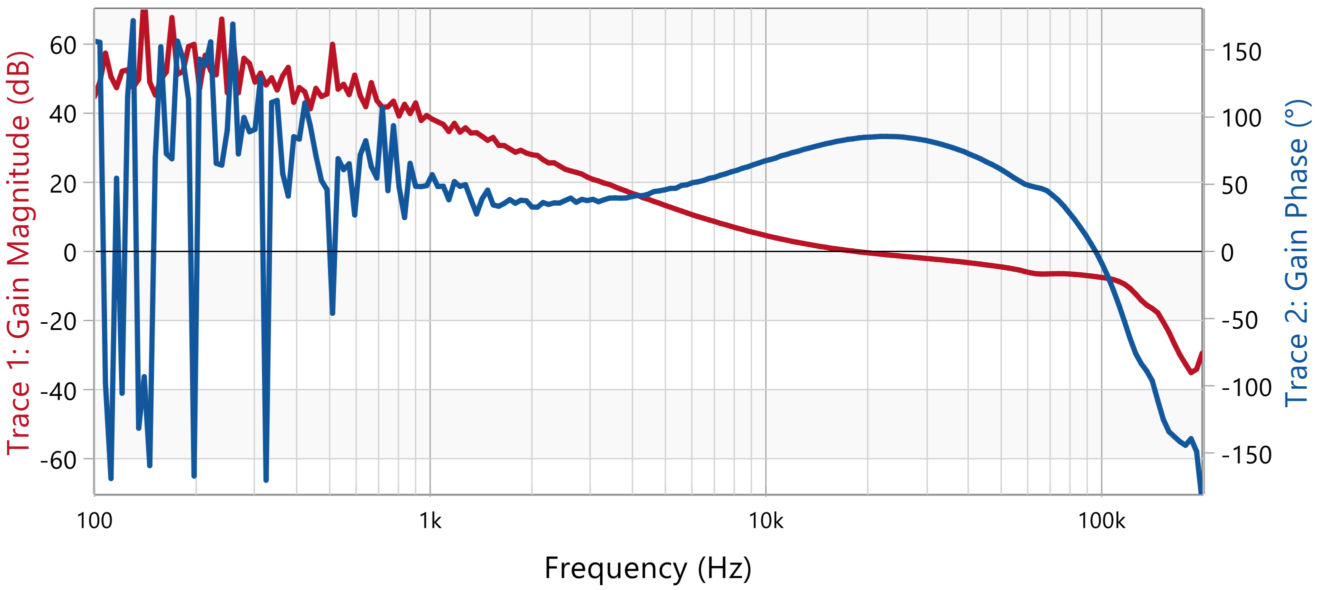
Bode 100 - Information Note

Noise in Loop Gain Measurements



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1 Introduction

Loop gain measurements are a commonly used method to determine the small-signal stability of control loops in electronic systems such as voltage regulators or switching power supplies.

Especially when measuring loop gain in switching power converters, the measurement result can be covered in noise at low frequency as shown in the figure below:

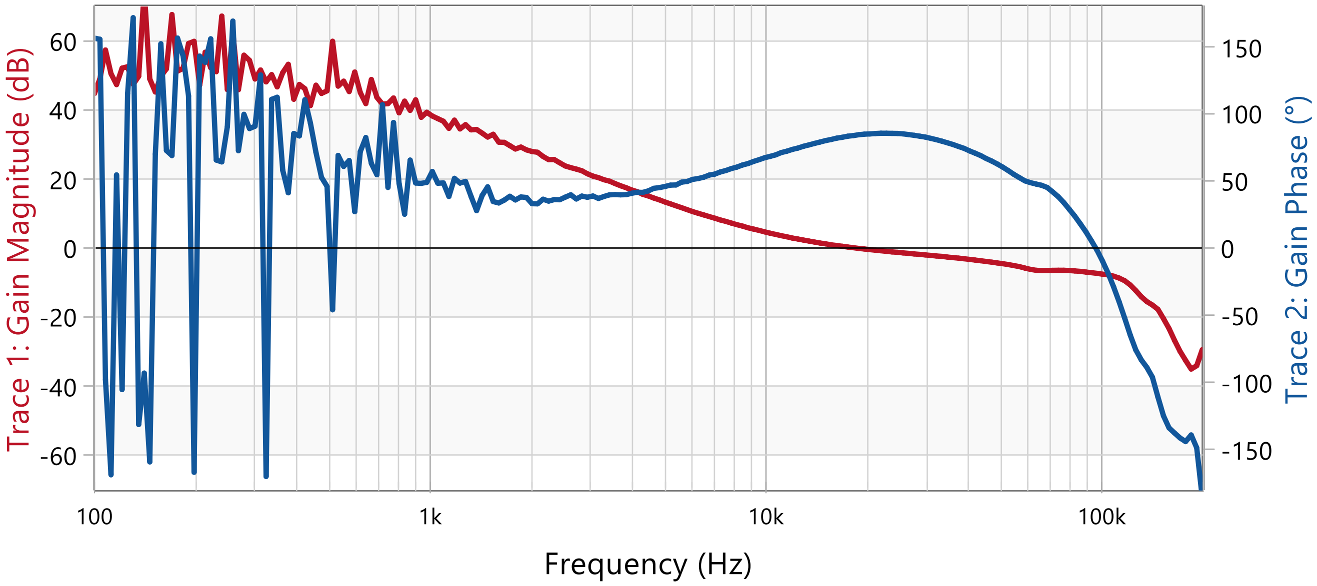

Figure 1: Noise at low frequency in a loop gain measurement

In this document, we want to provide an explanation where noise at low frequency comes from and how the measurement results can be improved.

2 Reasons for the Noise at Low Frequency

First, we would like to clarify that the noise at low frequency is not an issue of the Bode 100 device itself but lies in the nature of the measurement. The Bode 100 device offers excellent sensitivity and noise rejection at low frequencies due to its highly linear high-resolution narrow-band receivers. In this section, the reason for the noise at low frequency in a loop-gain measurement will be explained.

2.1 Loop Gain Measurement Basics

When measuring loop gain via the voltage injection method, an isolator is used to inject a disturbance sinewave into the feedback circuit. The isolator is required to isolate the measurement instrument from the dc-operating point of the device under test (DUT). Without an injection isolator, the ground-referenced instrument would short the dc voltage of the system to ground. In the following figure, the B-WIT 100 injection transformer is shown as the isolator and the Bode 100 vector network analyzer is used as the measurement instrument.

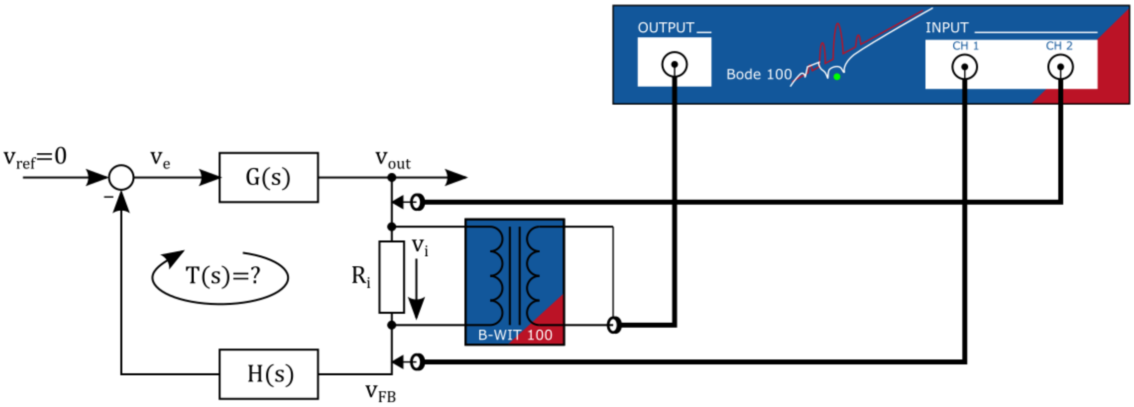

Figure 2: Noise at low frequency in a loop gain measurement

The injected disturbance voltage v_i is impressed differentially into the feedback loop via the isolator. The loop gain T is then evaluated by the vector network analyzer using $T = \frac{v_{CH2}}{v_{CH1}} = \frac{v_{out}}{v_{FB}}$. Note that only the ac signal portion is used for the measurement. Dc values are ignored and not directly relevant for the measurement of transfer functions. Please refer to our general Loop-Gain information note if you want to learn more about why and how this measurement works. The information note includes a summary of the mathematical explanation from "*Measurement of loop gain in feedback systems*" by R. Middlebrook.

An intuitive explanation including some important preconditions is given in the following:

- For the loop gain measurement, we assume that the signal flow in the control-loop system at the injection point is only in the forward direction and the information is provided in form of voltages. This is important because the disturbance is injected in form of voltage and only voltages are measured in this setup. Note that this precondition is fulfilled via the impedance condition ($Z_{out} \ll Z_{in}$) at the injection point.
- There must be no parallel signal path that can bypass the injection point. Any signal bypassing the injection point would falsify the measurement.

Using these conditions, one can imagine the following: If the controller or compensator sees a disturbance voltage at the feedback side (v_{FB}), it will try to reject it by reacting at the output of the system. The goal of the compensator is to keep the feedback node stable at the reference voltage without any ac variation. If there is high gain in the loop, the reaction of the system (v_{out}) will be high enough to compensate for the injected disturbance. At very high gain v_{FB} will be nearly zero and v_{out} will have nearly the same amplitude as the injected disturbance v_i. The ratio between v_{FB} and v_{out} equals the loop gain magnitude $|T|$ which is measured by the vector network analyzer.

2.2 Voltage Amplitudes in the Loop

As mentioned in the previous section, the ratio between v_{FB} and v_{out} equals the loop gain magnitude $|T|$. The maximum amplitude of the voltages v_{FB} and v_{out} however is defined by the amplitude of the injected disturbance v_i. The following figure shows the injected voltage v_i,the feedback node voltage v_{FB} and the system output voltage v_{out}. The feedback node is modelled as an input impedance Z_{in} and the system output as a voltage source with a finite output impedance Z_{out}:

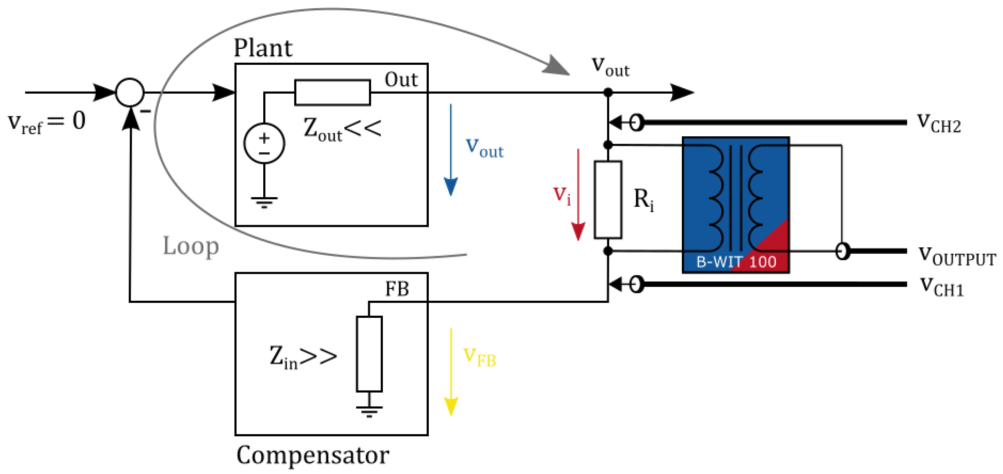

Figure 3: The voltage loop of the feedback system

The three voltages form a mesh where we can apply Kirchhoff's voltage law:

$$v_i + v_{out} + v_{FB} = 0 \quad (1)$$

Now let's consider the following three cases:

- At low frequencies where the loop has very **high gain**, nearly all the injected signal is visible at the system output ($v_{out} \approx \hat{v}_i$) and the ripple at the feedback node v_{FB} is very small.
- At the crossover frequency where the **loop gain is 1** ($0\ \mathrm{dB}$), both voltages v_i and v_{out} are of equal size (half the amplitude of the injected signal $v_{FB} = v_{out} \approx \frac{v_i}{2}$)
- At high frequencies where the **loop gain** is **smaller** than 1, most of the injected signal will be present at the feedback node ($v_{FB} \approx v_i$) whereas the output voltage will be stable with a very small ripple v_{out}.

The noise problems in loop gain measurements normally occur at low frequencies where the loop often has a high gain. The high gain is a design goal required to achieve good regulation at low frequency. It is generally achieved by adding an integrator to the compensator transfer function. So, let's try to analyze our noisy example.

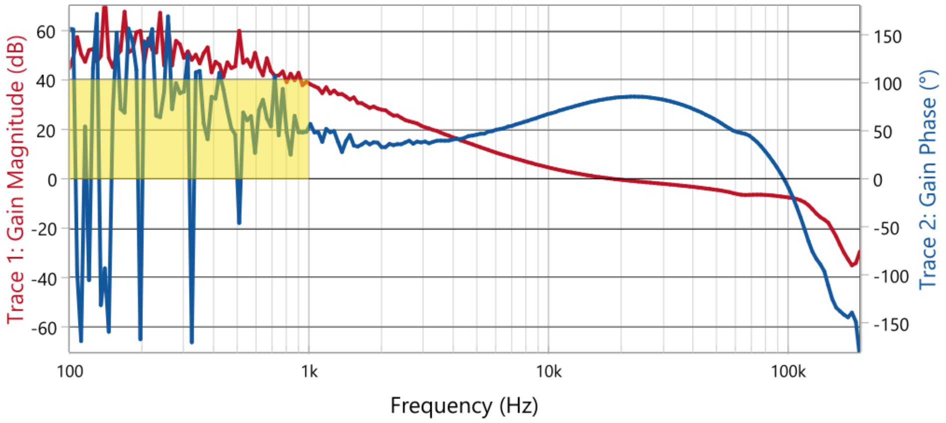

Figure 4: Noisy region and noise floor

From the figure above we can see that the noise floor is around $40\ \mathrm{dB}$. All the results that have a gain greater than $40\ \mathrm{dB}$ are very noisy and especially the phase measurement is covered in noise. At frequencies $>\ 1\ \mathrm{kHz}$, the gain starts to drop below $40\ \mathrm{dB}$, and the noise is getting less. Let's try to calculate the signal levels at a loop gain of $40\ \mathrm{dB}$ and an injection signal level of $-27\ \mathrm{dBm}$ like it was used in the measurement example shown in Figure 4.

2.3 Signal Amplitude

The injected signal size depends on the following three factors:

1. Signal level setting of the vector network analyzer
2. Attenuation of the injection transformer
3. Size of the injection resistor R_i

The B-WIT 100 is a 1:1 transformer with very low attenuation in the pass-band frequency ($< 0.15\ \mathrm{dB}$). In the following, we will therefore ignore the influence of the injection transformer.

With that assumption, the injected signal size only depends on the signal level setting of the Bode 100 and the injection resistor size. The internal source impedance of the Bode 100 is $50\ \Omega$. The following circuit shows the voltage ratios:

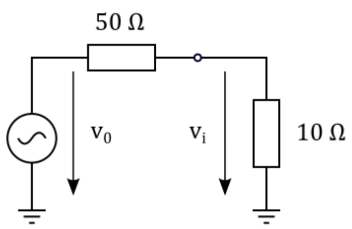

Figure 5: Injection voltage size

From the circuit with a $10\ \Omega$ injection resistor we can calculate the injection voltage v_i from the internal source voltage of the Bode 100 v_0 using:

$$v_i = \frac{v_0}{6} \tag{2}$$

The internal source voltage v_0 can be calculated from the signal level setting which is normally given in dBm. The unit dBm relates to the power dissipated in $50\ \Omega$. Zero dBm equals a power of $1\ \mathrm{mW}$ at a $50\ \Omega$ load impedance. The injection voltage v_i in Vrms can be calculated from the source level in dBm using the following equation:

$$v_0 = 2\sqrt{\frac{50\Omega \cdot 10^{dBm/10}}{1000}} \tag{3}$$

The following figure shows the injected signal level as root-mean-square voltage depending on the injection resistor value and the source level setting:

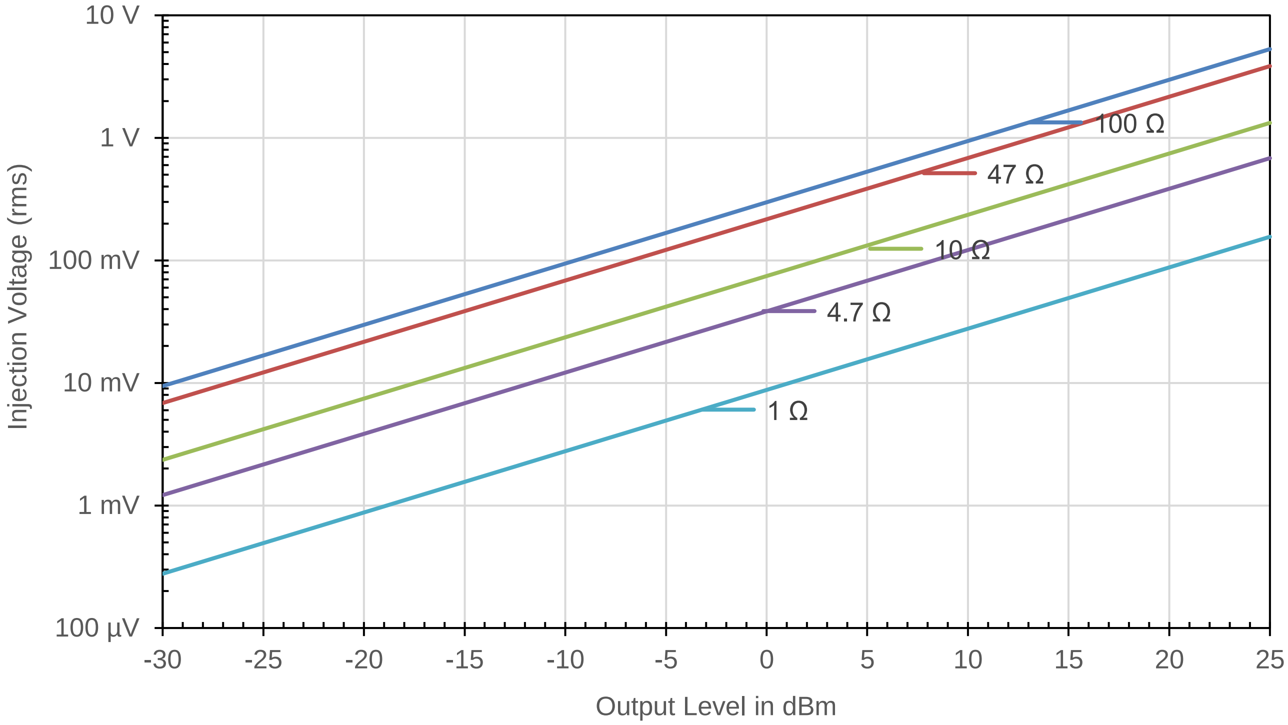

Figure 6: Injection voltage depending on source level and injection resistor

If we now calculate the injected signal size at the $-27\ \mathrm{dBm}$ setting with a $10\ \Omega$ injection resistor this results in $v_i = 3.3\ \mathrm{mVrms}$.

Now we can use the loop gain to estimate the two voltages. $40\ \mathrm{dB}$ can be considered high gain so most of the injected signal will be present at the output of the system $v_{out} \approx 3.3\ \mathrm{mVrms}$. At the feedback node, there will be $40\ \mathrm{dB}$ less signal. $40\ \mathrm{dB}$ equals a linear factor of 100. Hence the feedback node voltage will be roughly $v_{FB} \approx 33\ \mu\mathrm{Vrms}$. The challenge for the Bode 100 is to not only measure the amplitude of the $33\ \mu\mathrm{V}$ signal in the presence of the switching ripple but also measure the phase ratio between a $3.3\ \mathrm{mV}$ signal and a $33\ \mu\mathrm{V}$ signal in the presence of the switching ripple. In the example, the switching ripple at the output of the converter is around $25\ \mathrm{mVpp}$. The following figure shows the switching ripple of the converter on the left part of the image. The right image shows the $100\ \mathrm{Hz}$ disturbance injected by the Bode 100. v_{out} is the upper yellow trace. v_{FB} is the lower green trace. The Bode 100 shows a gain $> 40\ \mathrm{dB}$ but a phase difference cannot be resolved from the measurement because the v_{FB} signal amplitude is in the micro-volt region.

Figure 7: Switching ripple (left) and $100\ \mathrm{Hz}$ disturbance signal v_{out} and v_{FB} (right)

3 Fighting the Noise

The most important measurement is normally at crossover frequency where the phase margin of the system is measured. At that frequency, noise is generally not an issue because both voltages are of similar size, gain is 1 and phase can be resolved clearly. However, if a clear measurement curve is required also at lower frequencies, the following methods help to reduce noise on the measurement curve:

3.1 Select the right Probes

If you measure at dc voltage levels **below 50 Vdc**, **no** special **probes** are required. The Bode 100 inputs are ac-coupled and can withstand 50 Vdc when set to high-impedance mode.

If measurements need to be performed at voltage levels above 50 Vdc, the PML-111O passive 10:1 probe is suitable and provides low noise: https://www.omicron-lab.com/products/vector-network-analysis/accessories/pml-111o-passive-probe

Please note that normal 10:1 - 10 MΩ oscilloscope probes are not suitable to measure > 50 Vdc using the Bode 100.

For hazardous voltage levels, we recommend using a dedicated high voltage probe like the PHV 1000-O from PMK (https://www.pmk.de/en/phvomicron) or an active high-voltage differential probe for best protection. Note that active probes normally introduce more noise than passive probes.

3.2 Select Input Attenuators

The Bode 100 offers five different input attenuation levels to adjust the full-scale range of the inputs to your needs. Make sure to use the lowest possible input attenuator to get the best sensitivity. If the signal is too high, the Bode Analyzer Suite will show an overload warning.

Attenuator	Full-Scale Voltage
0 dB	100 mVrms
10 dB	316 mVrms
20 dB	1 Vrms
30 dB	3.16 Vrms
40 dB	10 Vrms

When measuring with the PML-111O 10 :1 probe, normally the 0 dB input attenuator is sufficient.

3.3 Reduce Receiver Bandwidth Setting

The Bode 100 measures frequency-selective with a narrow-band receiver filter. The narrower the filter bandwidth is chosen, the better the noise rejection but the longer the measurement time. If noise is present on the measurement curve, try reducing the receiver bandwidth (RBW) setting in the Bode Analyzer Suite (BAS).

A good starting value is 30 Hz. The measurement will still be fast but provide a high noise rejection. If it is still not enough, try using 10 Hz or even lower.

3.4 Increase Injection Signal Size

This is one of the most powerful measures to reduce noise. Increasing the injection signal size improves the signal/noise ratio during the measurement. If we think back to our example where 3.3 mVrms were simply not enough to generate a measurable signal, the most effective measure is to increase the injection signal at low frequencies.

Note: Often the injection signal level cannot be increased at all frequencies. Using a high injection level at high frequencies can cause non-linearities such as slew-rate limitations to distort the measurement. Please consider using the variable level over frequency (level-shaping) in these cases. For more information, please refer to our application notes and videos on loop gain or stability measurements.

The following figure shows a variable injection signal over frequency for the example shown in this document. An injection signal level of +13 dBm (333 mVrms) was chosen at low frequencies. At high frequencies the signal is reduced to the -27 dBm (3.3 mVrms) to avoid that non-linearities corrupt the measurement result.

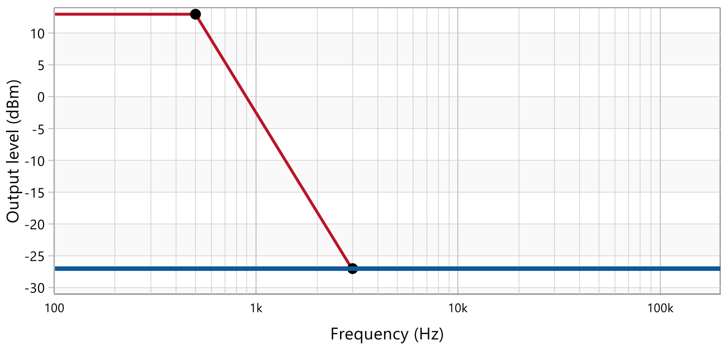

Figure 8: Shaped level - variable injection signal level over frequency

With this injection signal, the loop-gain curve gets clear and nearly noise-free as shown in the figure below:

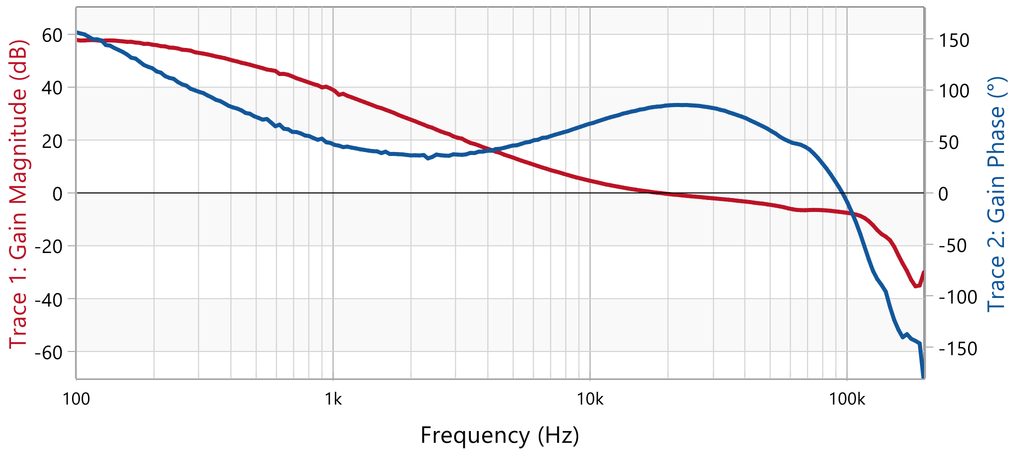

Figure 9: Clear loop-gain plot

As we can see from the figure above, the loop gain at 100 Hz is close to 60 dB which equals a linear factor of 1000. This means that the signal v_{out} will be 1000 times larger than the signal v_{FB}.

When looking at the 100 Hz signals using an oscilloscope (see figure below), the injected sinewave is clearly visible at v_{out} (yellow trace) but still not visible at v_{FB} because it is 1000 times smaller (around 3.3 mVrms). Still the Bode 100 can resolve the magnitude and phase difference of the two signals with very low noise in a very short time (18 s) which is remarkable.

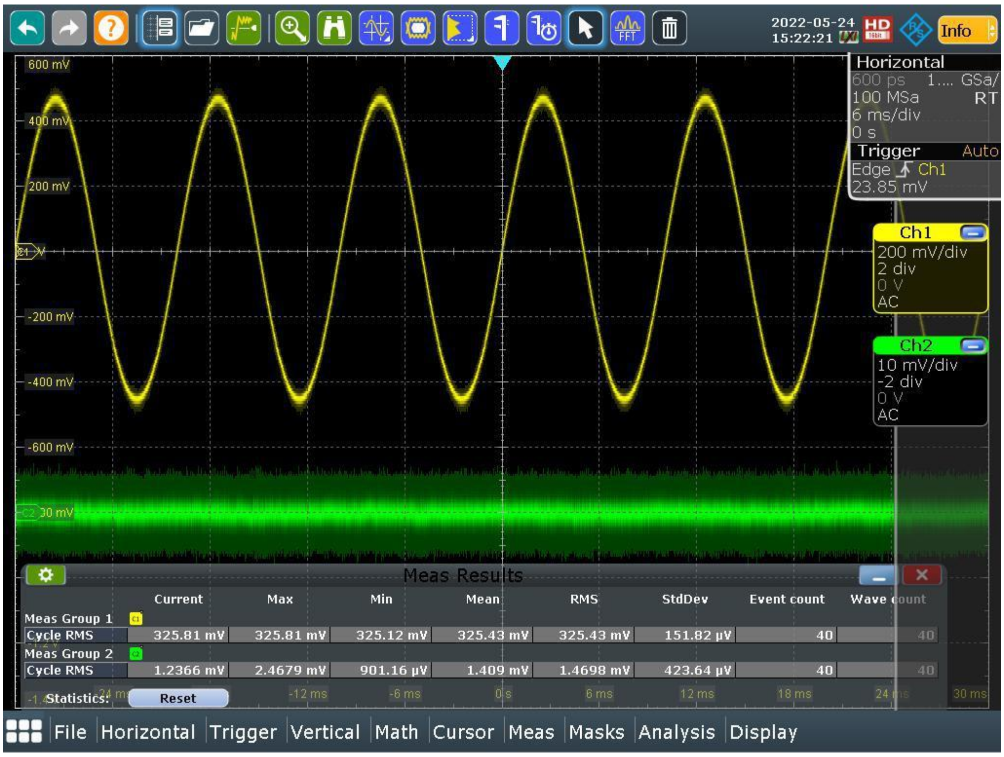

Figure 10: 100 Hz disturbance in time-domain

4 Conclusion

The Bode 100 does offer highest noise rejection, dynamic range, sensitivity, and linearity over the entire frequency range from 1 Hz to 50 MHz. It can measure gain and phase with low noise in situations where a sinewave cannot even be identified on an oscilloscope screen. The sweep shown in this document took only 18 seconds including 201 measurement points.

Loop gain measurements can be challenging especially when the loop has high gain. To get a clear plot in such a measurement one needs to inject sufficient disturbance voltage levels. The Bode 100 can generate up to 2 Vrms open-source voltage which equals 1 Vrms at a 50 Ω load. This is sufficient in many cases. If it is not enough, the B-AMP 12 amplifier can be used to increase the voltage levels by 12 dB respectively a factor of four to generate up to 8 Vrms open-source voltage.

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