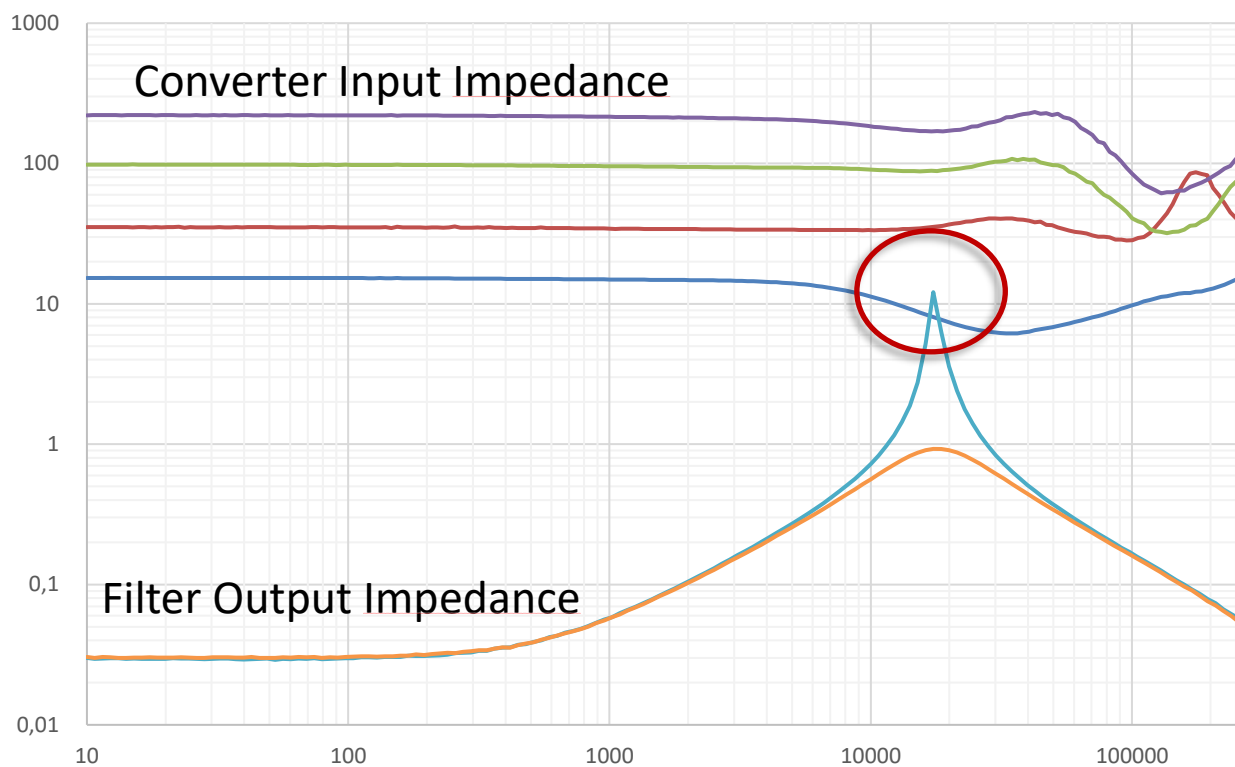# Bode 100 - Application Note

Input Impedance Measurements
for Stable Input-Filter Design

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Table of Contents

Note: Basic procedures such as setting-up, adjusting and calibrating the Bode 100 are described in the Bode 100 user manual. You can download the Bode 100 user manual at www.omicron-lab.com/bode-100/downloads#3

Note: All measurements in this application note have been performed with the Bode Analyzer Suite V3.11 Use this version or a higher version to perform the measurements shown in this document. You can download the latest version at www.omicron-lab.com/bode-100/downloads

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1 Executive Summary

This application note describes why the input impedance of a DC/DC power converter is an essential parameter for a stable system design. The theory of the filter stability problem is reviewed in section 2. To show that input filter instability is not only a theoretical problem but can also happen in real live, an experiment with a bad input filter design and its effect on system stability are demonstrated in section 3. Finally, different possible input impedance measurement setups are presented and discussed in section 4.

2 The Input Filter Can Degrade System Stability

The following figure shows a DC/DC converter having an input filter connected. The input filter is described by its voltage transfer function $H(s)$ as well as a finite output impedance $Z_{out}(s)$. For simplicity, the filter input voltage is supplied by an ideal voltage source V_{in}.
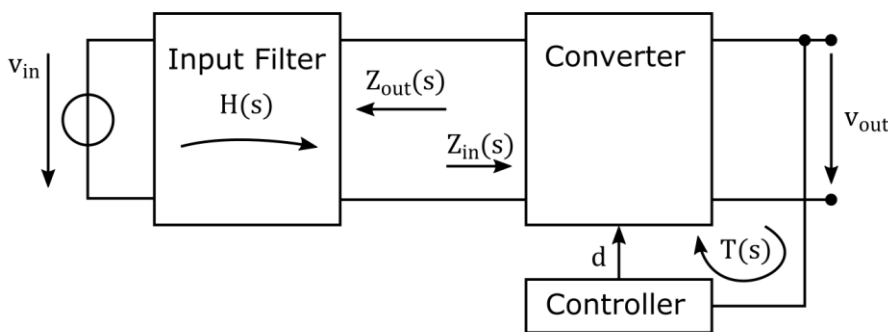

Figure 1: Power converter with input filter

Generally, one could assume that the input filter is a separate block that won't impact the converter at all. The fact however, that the filter and converter show non-zero output impedance and non-infinite input impedance can cause interactions between the two blocks that can degrade the performance of the DC/DC converter or even lead to instability of the converter control loop.

In the following we will have a look at the reasons for this interaction and how it can impact system stability.

2.1 Middlebrook's Extra-Element Theorem

The Extra-Element theorem from Middlebrook [1] describes, that the input filter can change or influence the converter transfer function and thus change the loop gain $T(s)$ which is an important measure for the control-loop stability of the DC/DC converter. In other words, adding an input filter can lead to control loop instability if certain conditions are met.

In the following we will have a quick look at the extra-element theorem and check how input-filter instability can be avoided.

Let's simplify the previously shown system to investigate the influence of the input filter on the converter. To do so, the input filter block is replaced by its output impedance Z_{out} and the loop is opened, leaving the converter duty-cycle to output transfer function $G_{vd}(s)$.
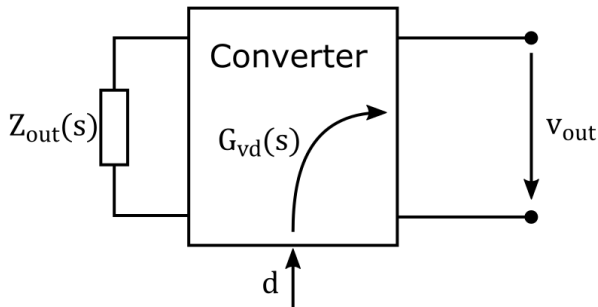

Figure 2: Simplified converter system

The extra-element theorem by R. Middlebrook [1] describes, how the transfer function of an electronic system changes, if a non-zero impedance is connected to the system. In our case, the plant transfer function $G_{vd}(s)$ of the converter changes as described in the following equation.

$$G_{vd} = G_{vd}|_{(Z_{out}=0)} \cdot \left(\frac{1 + \frac{Z_{out}}{Z_N}}{1 + \frac{Z_{out}}{Z_D}} \right) \tag{1}$$

Equation 1 contains the quantities Z_D and Z_N. Z_D is the input impedance of the converter running at a constant duty cycle (open-loop). $Z_D = Z_{in}|_{\hat{d}=0}$. Z_N is the input impedance of the converter assuming an ideal controller that keeps the output voltage constant at all frequencies $Z_N = Z_{in}|_{\hat{v}_{out} \to 0}$.

2.2 Reducing the Influence of the Input Filter

If $Z_{out} \ll Z_N$ AND $Z_{out} \ll Z_D$, then the modifying factor will be approximately 1:

$$\frac{1 + \frac{Z_{out}}{Z_N}}{1 + \frac{Z_{out}}{Z_D}} \approx 1 \tag{2}$$

This means that adding the input filter (Z_{out}) will NOT change the transfer function of the following converter system.

2.3 Simplified Black-Box Stability Criterion

Unfortunately, Z_N and Z_D are theoretical values that can only be derived by math or simulation. Especially Z_N is not measurable in a real-live system since an ideal controller is not feasible. If Z_N and Z_D are not known, only the black-box closed-loop input impedance Z_{in} can be easily determined by measuring the input impedance of the DC/DC converter running it under closed loop condition.

According to [2, Sec. 5.3] the following simplified condition is sufficient to prove system stability. In words; for guaranteed system stability, the output impedance of the input filter must be much smaller than the input impedance of the closed-loop converter.

$$|Z_{out}| \ll |Z_{in}| \tag{3}$$

If the phase information is available, even the full Nyquist stability criterion can be applied to the following ratio.

$$T = \frac{Z_{out}}{Z_{in}} \tag{4}$$

The closed-loop input impedance Z_{in} is not sufficient to prove that the input filter won't have an impact on the transfer function of the converter but it is sufficient to check for system stability.

In other words; by measuring converter input impedance and filter output impedance one can prove system stability but cannot conclude that the input filter won't change the system dynamic behavior.

2.4 Negative Resistance Causes Oscillation

The control loop of a converter keeps the output voltage V_{out} constant. Assuming a constant load R_{load} at the converter output, the output current I_{out} will also stay constant.

Constant output voltage and constant output current lead to constant output power P_{out}. If we assume that the converter has 100% efficiency, input power equals output power $P_{in} = P_{out}$.

Now let's assume the input voltage of the converter V_{in} increases by 10%. The converter regulation will keep the output voltage and therefore output power constant. The input power must stay constant as well since the converter cannot dissipate any power. To achieve this, the input current I_{in} must now decrease by 10%.

The fact that increasing the voltage causes the current to drop can be described as a **negative resistance**. A positive resistance would cause the current to rise if the voltage rises ($R = V/I$).

The negative input resistance of the DC/DC converter is a potential source of oscillation. The following equivalent circuit model shows how the inductance and capacitance of an LC input filter form a parallel resonance tank.
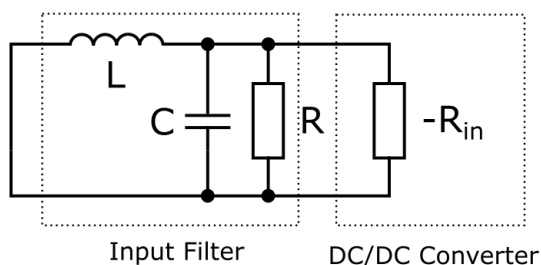

Figure 3: Small signal equivalent model of input stage

The parallel resonator is damped by the damping resistor R. Now, if the negative input resistance of the DC/DC converter equals the damping resistor $R = -R_{in}$ it will cancel or neutralize the damping. What is left will be a parallel LC resonator with zero damping that can continuously oscillate with the resonance frequency $f_{res} = \frac{1}{2\pi\sqrt{LC}}$.

3 Experimental Verification

The input filter stability problem is well known in theory but does it really happen in a real live application?

The fact that the loop bandwidth is generally limited helps to avoid negative resistance oscillation. Negative resistance only appears at frequencies where the loop gain of the converter is sufficiently high and the converter shows good regulation. Depending on the speed of the control loop this frequency can be between hundreds of Hz up to decades of kHz.

The negative resistance oscillation occurs if the resonance frequency of the input filter falls into the negative resistance region of the converter. This means that the resonance frequency of the filter must be well below the crossover frequency of the converter. This generally only happens if either the control loop is very fast or the input filter is rather big.

3.1 DC/DC Converter Under Test

To show that the input filter however can dramatically degrade system performance we perform the following experiment based on a synchronous Buck converter evaluation board (ADM00467 from Microchip[1]). The board features two DC/DC step down converters as shown below:
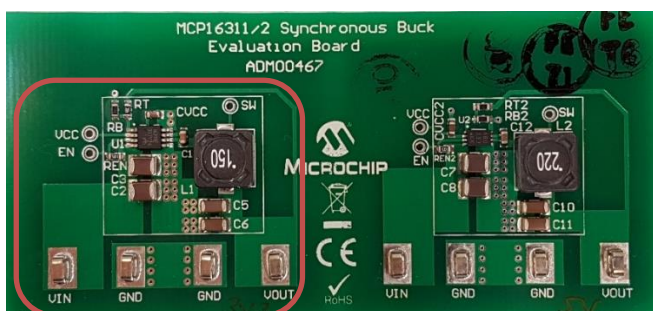

Figure 4: Converter Under Test

The following figure shows the circuit diagram or schematic of the converter including the component values.
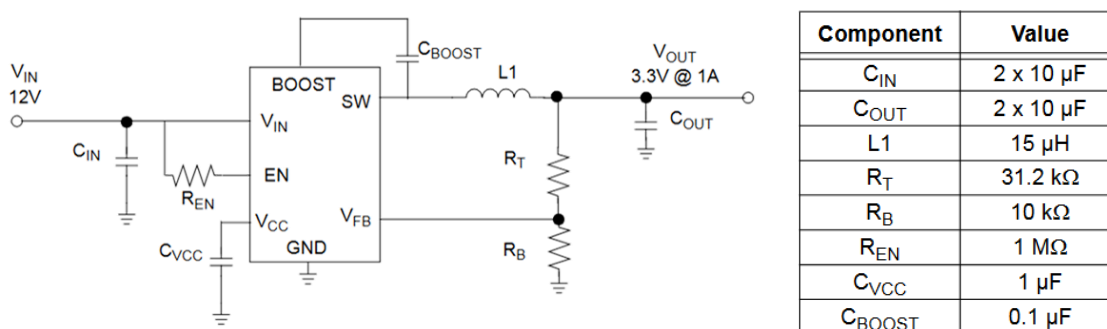

Component	Value
C_{IN}	2 x 10 µF
C_{OUT}	2 x 10 µF
L1	15 µH
R_T	31.2 kΩ
R_B	10 kΩ
R_{EN}	1 MΩ
C_{VCC}	1 µF
C_{BOOST}	0.1 µF

Figure 5: Converter schematics and part list from the manufacturer's datasheet

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[1] Thanks to Andreas Reiter from Microchip for providing us the boards

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3.2 Adding an Input Filter to Reduce Input Current Ripple

Let's assume we want to reduce the input current ripple by adding an input filter. The following figure shows the converter schematic without any input filter. Note that the input capacitors were removed as well.
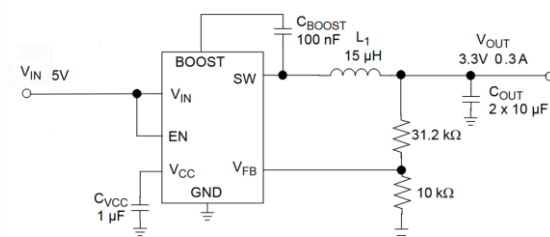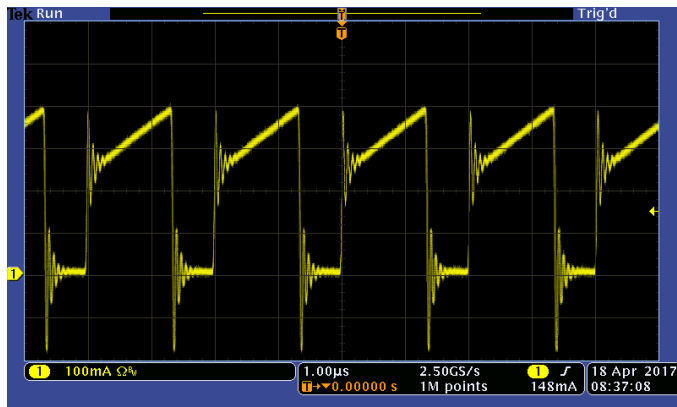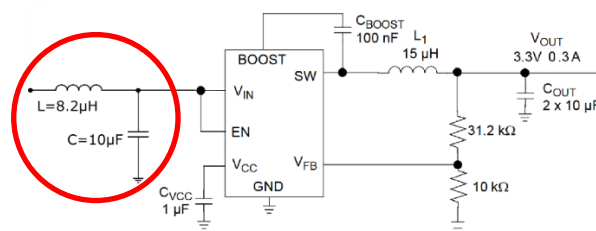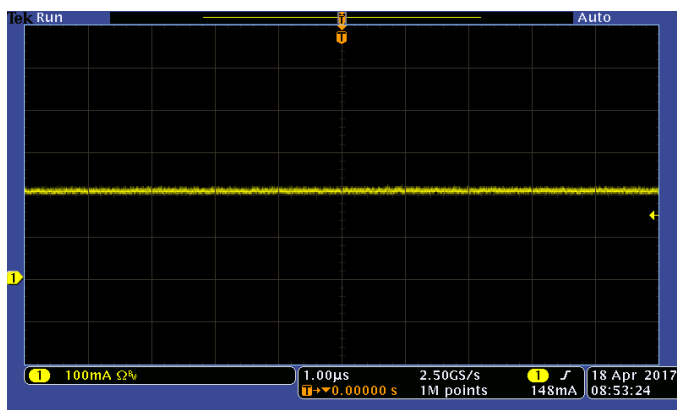
Converter without input filter

Figure 6: Input current ripple without input filter

The input current shows a 400 mA peak current ripple which is natural for a buck converter that has no inductance prior to the power switch. To flatten the input current ripple, an input filter composed of an inductance ($L = 8.2\ \mu H$) and a capacitor ($C = 10\ \mu F$) was added to the system. The following figure shows the input filter on the board:

Figure 7: DC/DC converter with mounted input filter

The input filter causes the input current to flatten perfectly. Only the DC input current of

$$I_{in} = I_{out}\ \frac{V_{out}}{V_{in}} = 300\ mA\ \frac{3.3V}{5V} = 198mA$$ is left at the input.

Converter with input filter connected

Figure 8: Input current ripple with input filter

3.3 Influence on the Stability of the Converter

The input filter has significantly flattened the input current which can be very advantageous, considering system noise that can couple from the power bus to sensitive circuits. Furthermore, the EMI emissions will be reduced since the current ripple is limited to the small region between the input filter and the converter.

To check if the filter has an influence on the stability of the DC/DC converter the loop gain of the DC/DC converter was measured via the voltage injection method. Therefore, the Bode 100 vector network analyzer and the B-WIT 100 injection transformer is used.

The following figure shows the measured loop gain of the converter with and without the input filter.
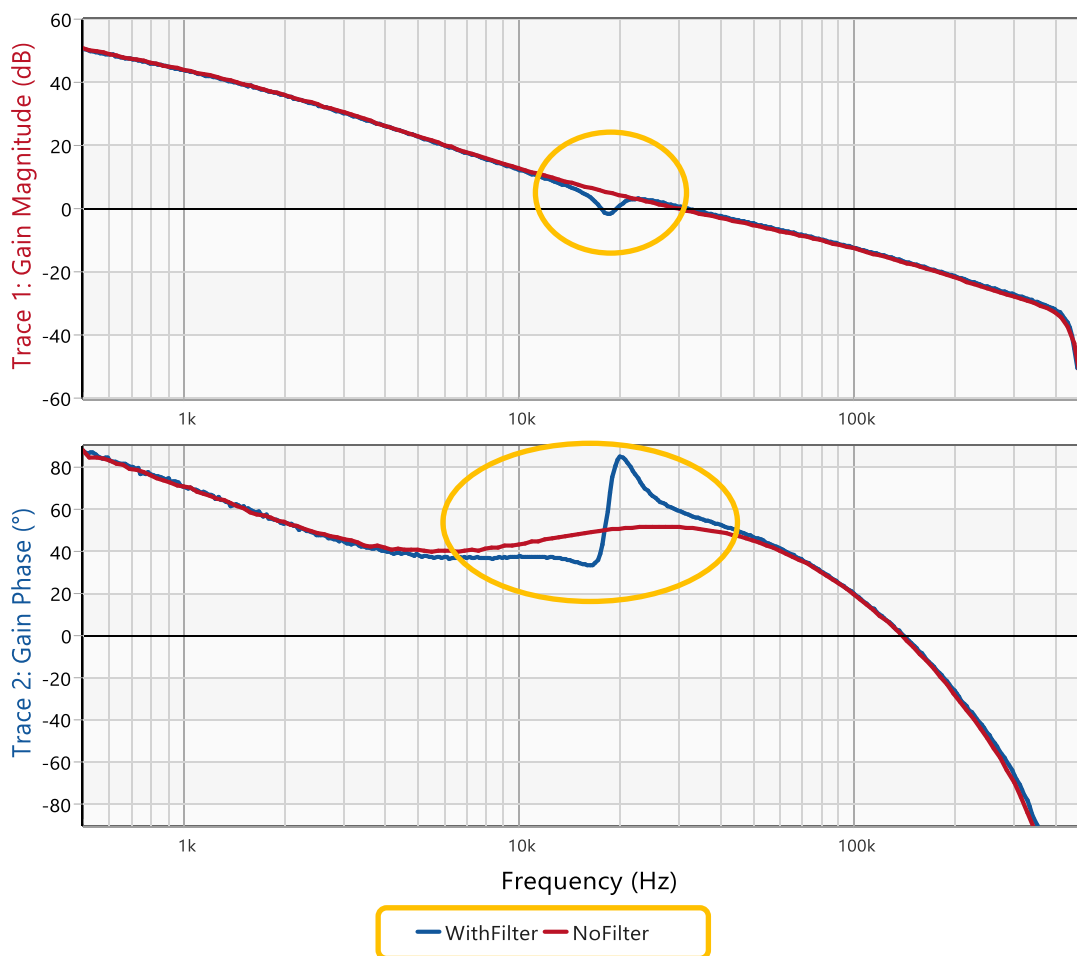

Figure 9: Impact of the input filter on the Loop Gain (measured using Bode 100 and B-WIT 100)[2]

The measurement shows that the input filter has a dramatic influence on the loop gain curve. Adding the filter, leads to an additional crossover frequency around 17 kHz and to a degradation of phase margin around 35° at the new crossover frequency.

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[2] The input voltage of the DC/DC converter was set to 4 V, output voltage 3.3 V at 300 mA

3.4 Influence on the Transient Response

To check how the degraded loop gain impacts the transient response a small-signal load step test was performed. 50 mA load steps were generated using a Picotest J2111A current injector and a Picotest G5100A arbitrary waveform generator. The following figure shows the transient response without input filter on the left-hand side and the transient response with input filter on the right-hand side.
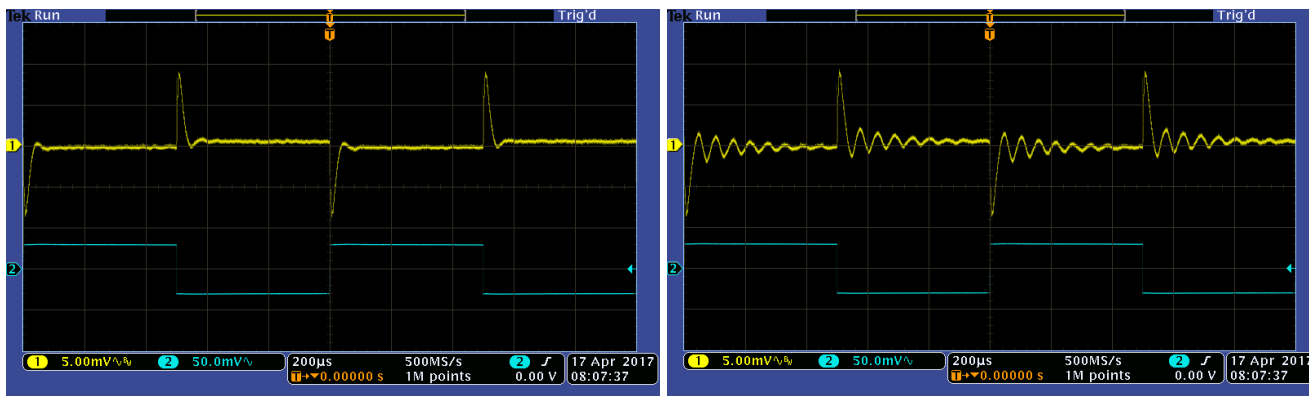

Figure 10: Impact of the input filter on the transient response[3]

The transient response with input filter shows clearly degraded performance. Excessive ringing at approximately 17 kHz appears after each load step. This ringing is not present without the input filter. Note that the ringing is undesired and can significantly degrade performance when powering a sensitive circuit.

3.5 Impedance Ratio

The following figure shows the measured converter input impedance at different input voltage levels. In addition, the measured output impedance of the input filter (shortcut on the input) is included:
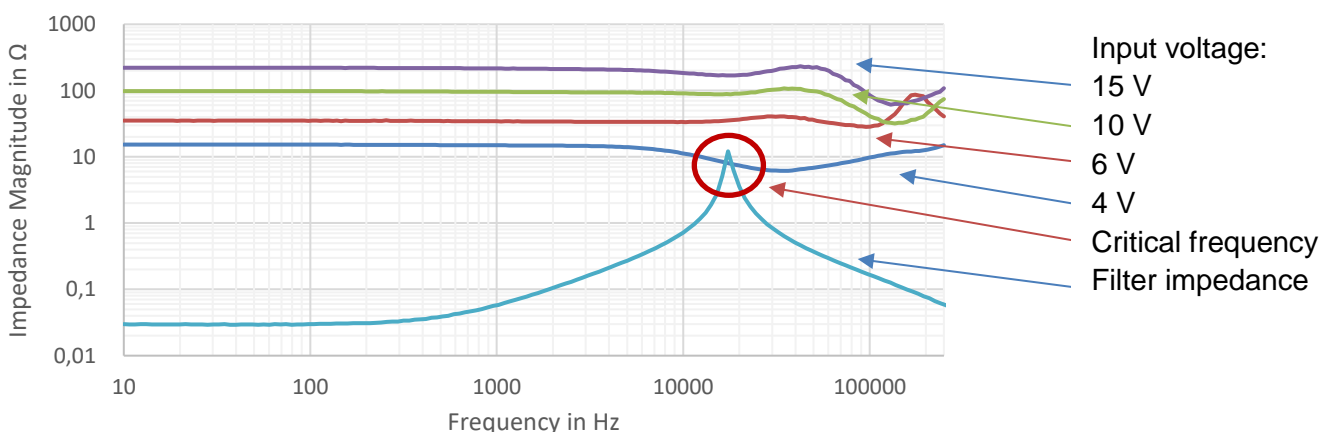

Figure 11: Converter input impedance an input filter output impedance (measured using Bode 100 VNA)

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[3] 1:1 voltage probes and "averaging on" to remove the switching ripple from the waveform

Figure 11 clearly shows that the measured closed-loop input impedance of the converter and the output impedance of the filter intersect at $\approx 17\ kHz$. The input filter impedance at resonance peaks above 10 Ω, whereas the converter input impedance is below 10 Ω at an input voltage of 4 V. The impedance peak of the input filter resonance is clearly the reason for the system oscillation at 17 kHz.

3.6 Damping the Input Filter

By adding a resistive loss element to the filter circuit, the LC resonance of the input filter can be damped. The damping will reduce the impedance peak at resonance. The lower peak at resonance makes it easier to separate the impedance curves at all frequencies. Since the damping element must not reduce the system efficiency, it must not add resistance at DC respectively at low frequencies. Two of the simplest ways to damp an LC input filter are shown below:

Figure 12: R-C parallel damping and R-L parallel damping elements

Certainly, one tries to reduce the size of the needed damping elements as much as possible. Optimized damping of the input filter is discussed widely in literature such as [3], [4] and [5].

The following figure shows the impedance magnitude for the undamped and the damped input filter that was used during the lab-experiment.
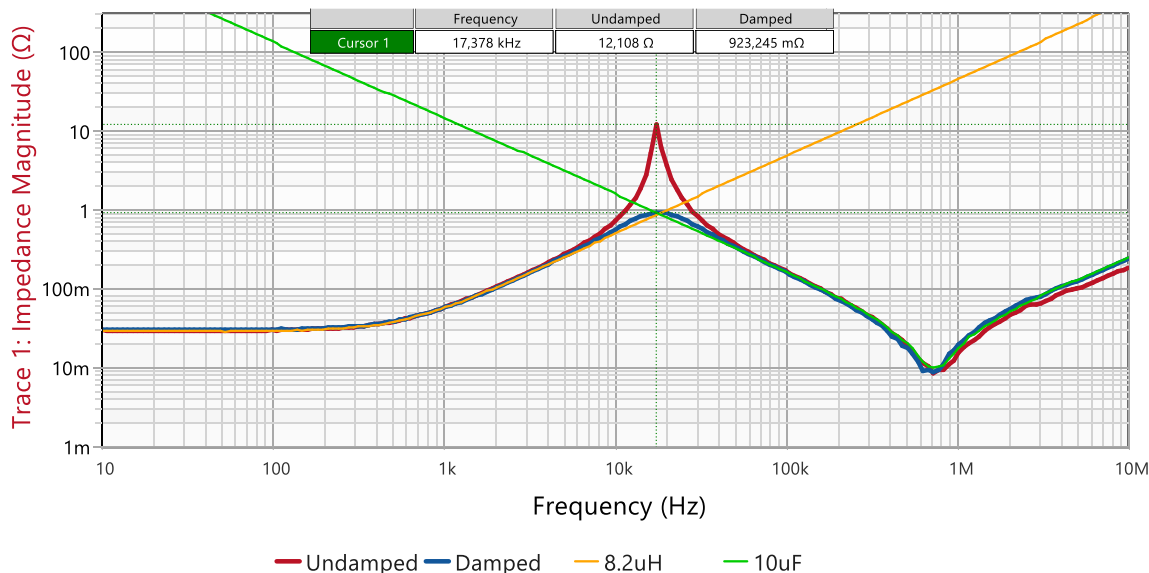

Figure 13: Resonance peak of the undamped and damped filter (measured using Bode 100 and B-WIC)

Figure 13 shows that the impedance peak was lowered from ≈12 Ω to ≈1 Ω by adding a damping element to the filter. The impact on the loop gain of the converter was also lowered as shown in the following figure:
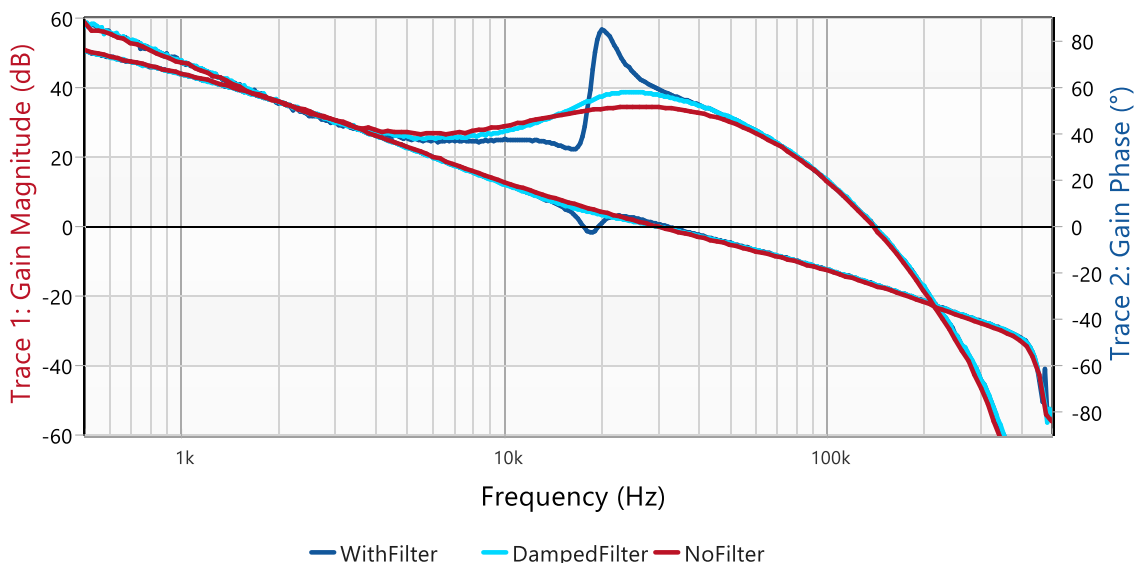

Figure 14: Damping the input filter reduces impact on loop gain

The loop gain does show that the second crossover frequency that was added by the input filter disappears when the input filter is damped. The damping also recuperates the transient response as shown in the following figure.
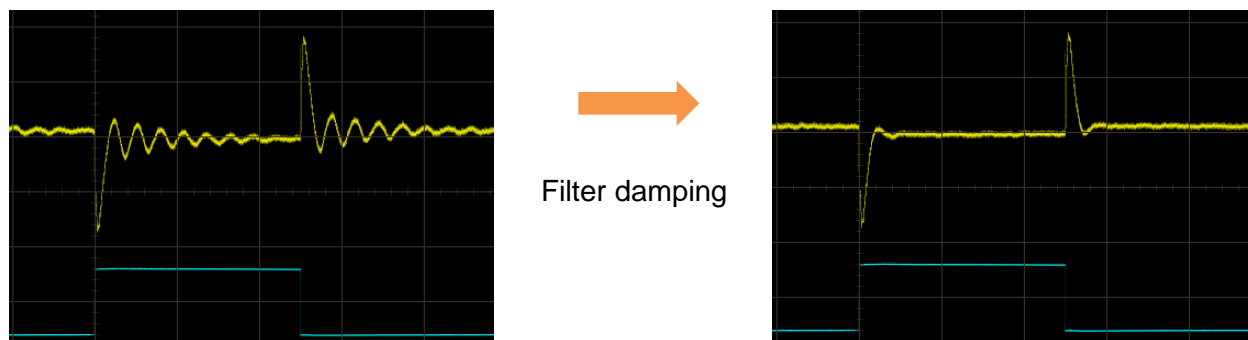

Figure 15: Improving transient response by damping the input filter

4 Measuring the Input Impedance of a DC/DC Converter

The AC input impedance of a DC/DC converter can be measured using various methods. The input impedance measurement of a 100 mW converter will require a completely different test-setup than the input impedance measurement of a 100 kW converter. The basic measurement concept however generally stays the same for all power levels. In the following the Voltage/Current method is explained in detail.

4.1 Voltage / Current Method

The input impedance is defined as the quotient of AC input voltage and AC input current.

$$Z_{in} = \frac{\hat{v}_{in}}{\hat{\imath}_{in}}$$
(5)

To be able to measure the input impedance an AC disturbance must be added to the DC supply voltage. Then the input impedance can be evaluated by comparing the size of voltage ripple and corresponding current ripple as shown in equation 5.

The following figure shows the basic test setup that can be used to measure the input impedance of the DC/DC converter (DUT[4]) using the Bode 100 vector network analyzer / frequency response analyzer.
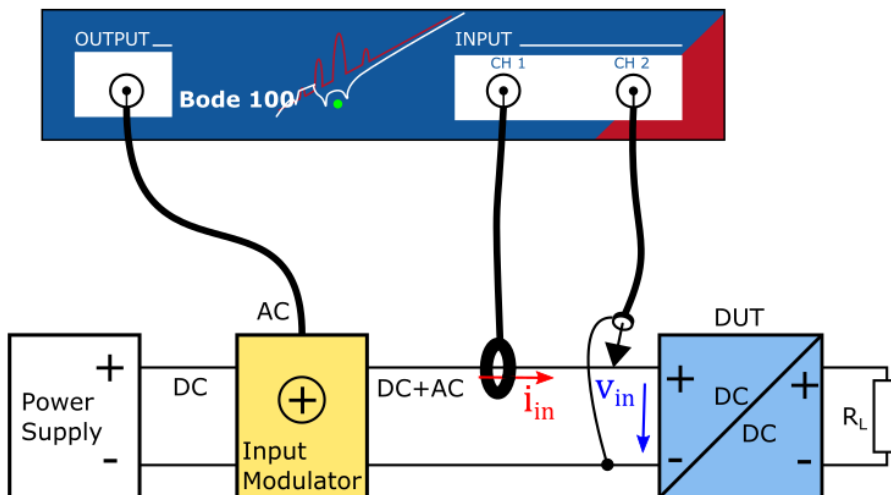

Figure 16: Input impedance measurement setup (Using Bode 100 VNA)

By connecting the Bode 100 in this way and choosing the "Voltage/Current" impedance measurement mode in the Bode Analyzer Suite software, the Bode 100 measures the input impedance of the DUT by performing the complex division $Z = \frac{V_{CH2}}{V_{CH1}}$. The used stepped sine-wave frequency response measurement method offers the high sensitivity and noise-rejection needed to achieve high-dynamic-range results on DUTs that generate a lot of switching noise.

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[4] Device Under Test

4.2 Voltage/Current Measurement Mode

The Bode Analyzer Suite offers the Voltage/Current measurement mode that is perfectly suitable for input impedance measurements. The measurement mode features:

- Direct impedance result displays (Rs, Cs, Cp, Lp, Ls, Magnitude, Phase etc…)
- Bode-Plot or Nyquist/Polar Plot
- Two different calibration methods (Thru or Open/Short/Load)
- Flexible hardware setup for various measurement setup possibilities

The flexible hardware setup dialog allows the user to configure the Bode 100 VNA in an optimal way for each measurement setup or probe-configuration. The following figure shows the hardware setup of the Voltage/Current measurement mode available in Bode Analyzer Suite 3.0 or newer.
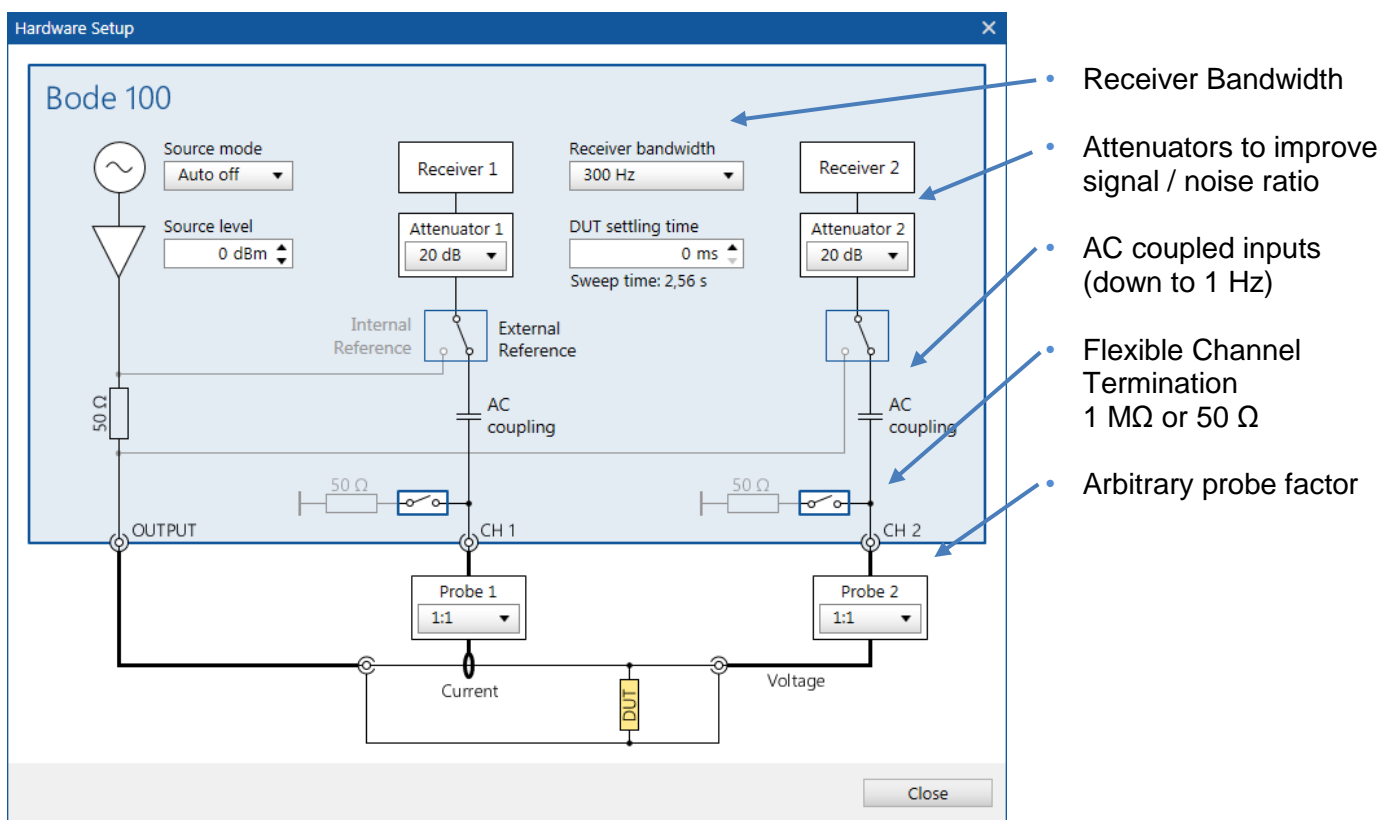

Figure 17: Hardware setup of the Voltage/Current measurement mode (Bode Analyzer Suite 3.X)

The following settings are important for any input impedance measurement:

- Receiver bandwidth: Smaller values increase noise-rejection but lower sweep speed
- Attenuator: Input receiver sensitivity can be adjusted to match the size of the AC measurement signal to improve signal/noise ratio. Input receiver full-scale sensitivity can be adjusted from 100mVrms (0dB attenuator) to 10Vrms (40dB attenuator)
- The inputs are AC coupled for measurement down to 1 Hz rejecting the DC portion of the signal
- Channel Termination can be set to 50 Ω or 1 MΩ depending on the used probes
- An arbitrary probe factor settings allows to compensate a probe factor and can be used to reverse the phase by entering negative values

4.3   Modulating the DC Input Signal

Depending on the power level of your application, this is the trickiest part of the entire input impedance measurement. The challenge is to modulate the DC supply proportionally to the Bode 100 output signal such that the AC signal is added to the DC supply. Depending on the voltage level and power level of the DUT this can be quite easy or very challenging.

In the following we will have a closer look at the following measurement methods:

- Modulate the DC supply using a line injector such as the Picotest J2120A
- Modulate the DC supply line using a linear power amplifier featuring a DC offset
- Injecting to the DC supply via inductive coupling
- Injecting to the DC supply via capacitive coupling

Note that there are many more measurement methods possible as shown in e.g. [6].

4.3.1   J2120A Line Injector from Picotest

The J2120A line injector from Picotest (www.picotest.com) is an easy-to-use injection device that allows to impress an AC disturbance signal on a DC supply voltage. The maximum usable voltage is 50 V_{DC} at a maximum current of 5 A_{DC}. If your DUT fits into that power level, the J2120A is a great choice.

The following figure shows the measurement setup using the Bode 100 in combination with the J2120A from Picotest.
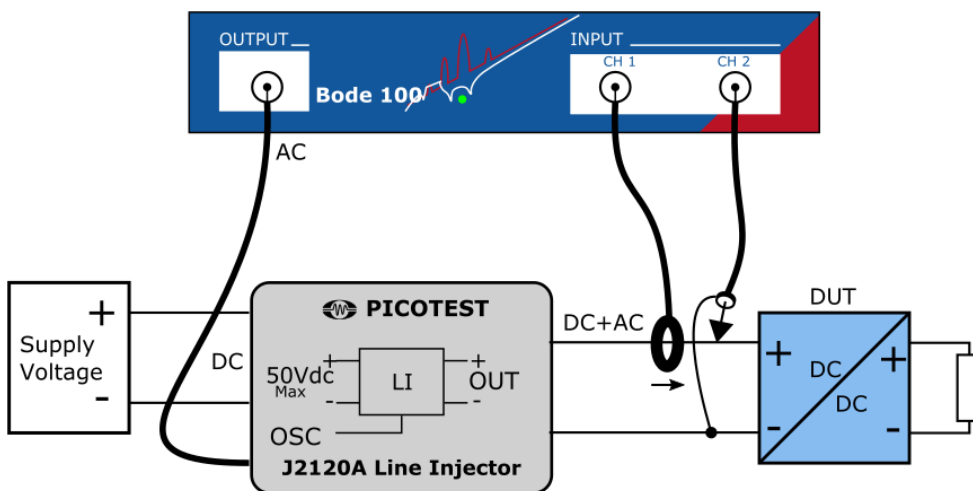

Figure 18: Input impedance measurement setup using the Picotest J2120A Line Injector

Note that the J2120A introduces a DC loss as well. Therefore, the DC input voltage of the DUT must be monitored during the measurement to ensure stable operating conditions.

4.3.2 Configurable Power Amplifier

An alternative measurement approach replaces the power supply by a powerful linear voltage-amplifier. The amplifier must be able to deliver the DC voltage and current required to drive the converter under test. In addition, it must have a sufficiently high upper frequency limit to support the frequency range of interest for the input impedance measurement. The following figure shows an example measurement setup using a power amplifier from Rohrer (http://www.rohrer-muenchen.de/). The amplifier delivers the DC power as well as the AC measurement signal.
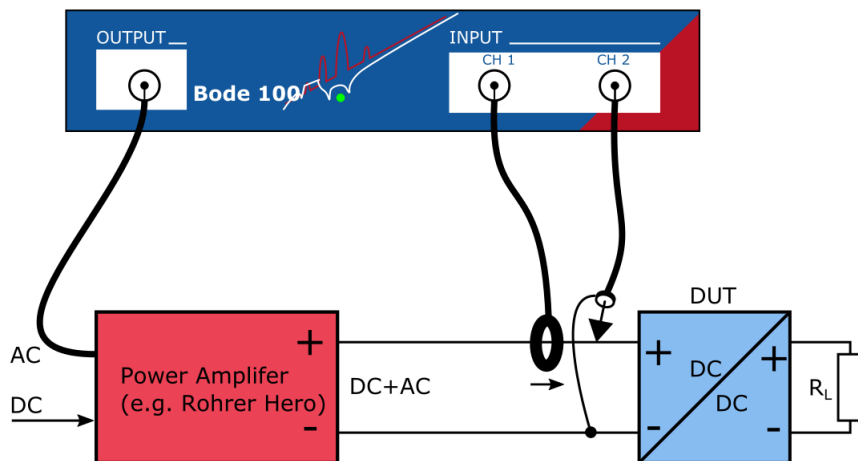

Figure 19: Input impedance measurement setup using a power amplifier

The advantage of this method is its scalability. Amplifiers can be found up to the kW power range. Some amplifiers do even provide a current-monitor output which further simplifies this setup by avoiding the need of an additional current probe. In addition, this is the only setup that provides control over the absolute size of the amplitude of the AC measurement signal.

4.3.3 Capacitive or Inductive Injection

If no suitable power amplifier can be found, the AC measurement signal can also be injected onto the DC supply using inductive or capacitive coupling mechanism. The following figure shows a measurement setup that uses an inductive injection probe and a power amplifier (B-AMP 12).
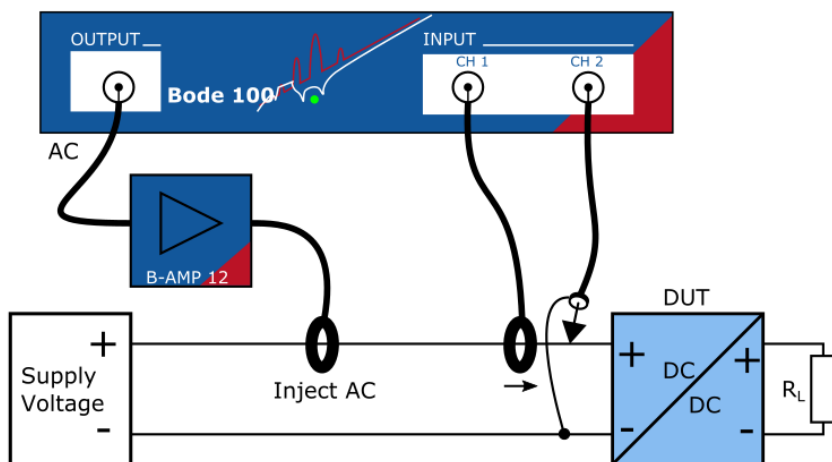

Figure 20: Input impedance measurement setup using inductive signal injection

Alternatively, capacitive coupling can be used as well. The capacitor is used to block the DC voltage from arriving at the injecting amplifier or measurement equipment as shown in the figure below.
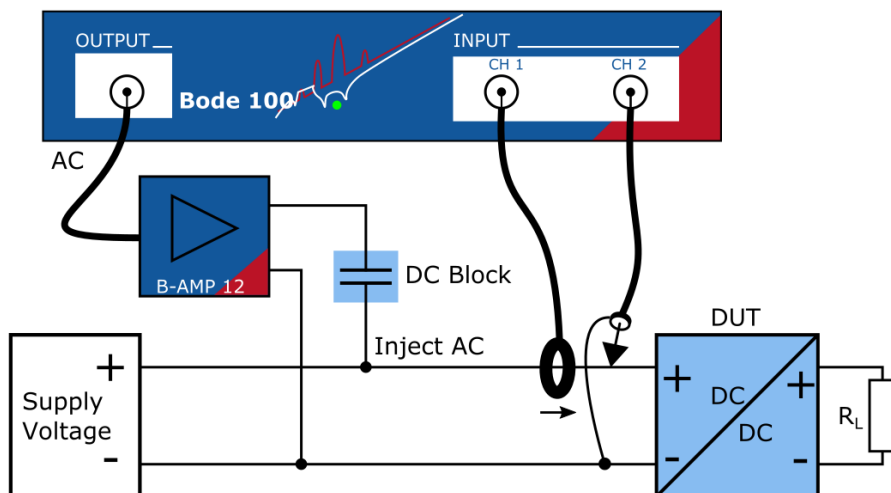

Figure 21: Input impedance measurement setup using capacitive signal injection

The above-mentioned injection methods might require a higher power level than the +13 dBm maximum power of the Bode 100. Therefore, the B-AMP 12 power amplifier was included in the measurement setup. B-AMP 12 provides additional 12 dB of amplification resulting in a maximum injecting power of 25 dBm (316 mW). Certainly, any third-party amplifier can be used to increase the injection power even further.

The advantages of these injection methods is their full scalability. Depending on the choice of the inductive or capacitive injection methods, nearly any power level can be measured. The inductive injection offers further on the advantage of galvanic isolation. When suitable probes are used, a fully isolated test system can be employed using inductive injection. Note that injection clamps or current transformers needed for these measurements are hard to find or need to be custom-made.

Hint: It might be advantageous to provide a low-impedance path to the injected signal on the supply side as shown in the following figure. This will improve the results especially at higher frequencies.
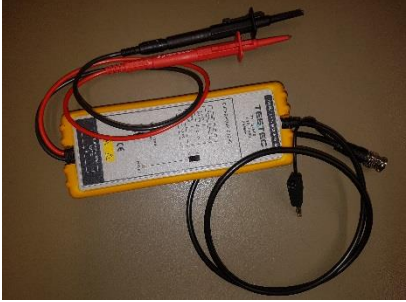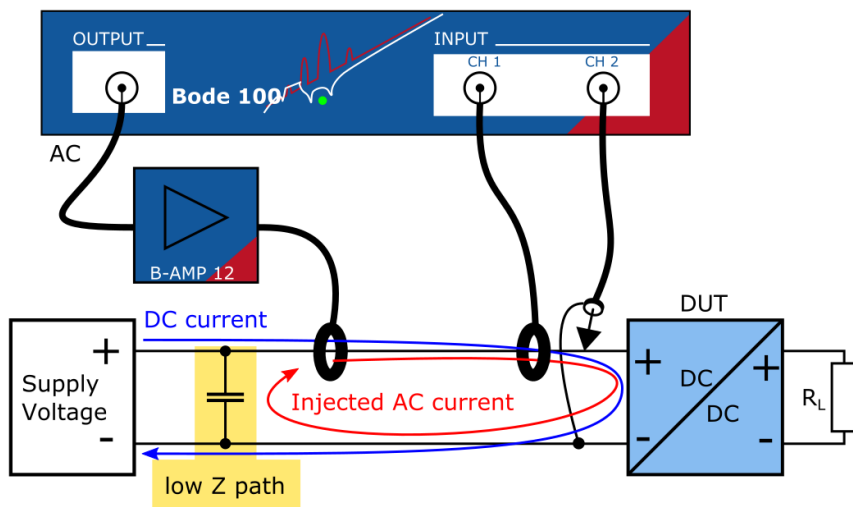

Figure 22: Providing a low-impedance path for the injected signal

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4.4   Measuring the AC Voltage

To measure the input impedance of the DUT, the voltage at the DUT input port must be measured at Channel 2 of the Bode 100. Only the AC voltage is of interest but the DC voltage is present as well. The inputs of the Bode 100 are AC coupled up to 50 V_{DC}. Hence, DC voltages up to 50 V can be directly connected to the Bode 100 Channel 2 using a 1:1 connection. To reduce noise, coaxial cable connections are recommended.

NOTICE
Ensure that Channel 2 input is set to 1 MΩ input impedance (high impedance). At 50 Ω termination it will only withstand 7 V_{RMS}

The following table shows some of the possibilities that can be used to measure the voltage. Bandwidth limits are generally not a concern for the voltage probing method. All the connection methods below achieve a bandwidth of 25 MHz or higher.

Connection	Example	Price	Isolation	Noise
1:1 BNC Cable		Low	No	Lowest
10:1 Passive Probe		Medium	No	Medium
Active Differential Probe (High Voltage)		High	Yes	Highest

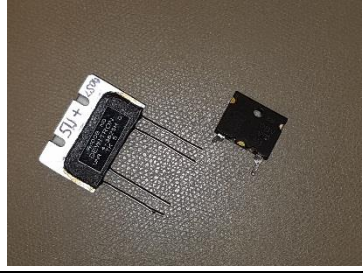| NOTICE |
| --- |
| Do not apply more than 50 V_{DC} to the input channels of Bode 100!
Even a **passive 10:1** probe with 10 MΩ input impedance **cannot** be used to **increase** the **DC capability** since the inputs are AC-coupled! |

4.5 Measuring the AC Current

Besides the input voltage, the input current must be measured as well. As with the voltage signal the current contains AC and DC as well. Only the AC current must be measured. The DC current is not directly relevant for the impedance measurement but will complicate the AC current measurement since the DC current might saturate the used current-monitor respectively current-transformer.

The following table contains an overview on different current probing methods and their properties:

Probing	Example	Price	Isolation	Bandwidth	DC Sensitive
Hall-Effect Probe (BNC connector output)		High	Yes	f_{min}: DC f_{max}: 20-50 MHz	Compensated
Active Rogowsky Current Probe		Medium	Yes	f_{min}: Hz…kHz f_{max}: 20-30 MHz	No
Current Transformer (Current Monitor)		Medium	Yes	f_{min}: Hz…kHz f_{min}: MHz	Yes (Core Saturation)
Shunt Resistor		Low	No	f_{min}: DC f_{max}: MHz	Yes (Power Limit)

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4.6 Calibrating the Test Setup

Depending on the frequency range of interest and/or the quality of the used probes a calibration (compensation) might be necessary. Calibration removes the frequency responses of the voltage probe and the current probe by measuring a known quantity.

Note: It is always ideal to use probes that have a sufficiently high bandwidth and sufficiently high accuracy such that no software calibration or compensation has to be used. This will generally result in lowest noise and highest dynamic range measurement. However, if only limited probes are available, software calibration can overcome probe limitations.

The Voltage/Current measurement mode of the Bode Analyzer Suite supports two different calibration methods. The following figure shows the calibration dialog of the Bode Analyzer Suite in the Voltage/Current measurement mode.
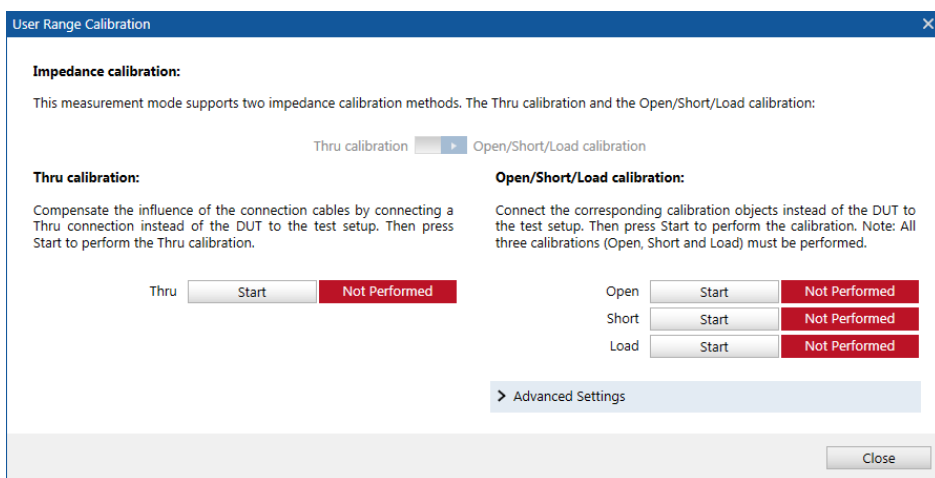

Figure 23: Thru or Open/Short/Load calibration can be applied in Voltage/Current mode

4.6.1 Thru Calibration

Thru calibration is the simplest way to compensate for the non-ideal frequency response of the voltage probe and the current probe. During Thru calibration, the same signal must be provided to both, the current probe and the voltage probe. The easiest way to achieve this is to connect a 1 Ω resistor during calibration. At the 1 Ω resistor 1 A will result in 1 V which is the same. The following figure depicts this connection setup during Thru-calibration.
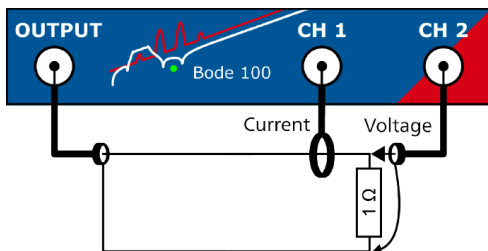

Figure 24: Thru calibration in Voltage/Current measurement mode

The advantage of this method is that only one calibration measurement must be performed. Furthermore, the connection setup is quite simple. The disadvantage is that a 1 Ω resistor also contains inductance. Let's assume that a 1 Ω resistor that has 10 nH of parasitic

inductance is used. This will introduce a measurement error of 6 % at 1 MHz due to the reactance added by the 10 nH parasitic inductance.

4.6.2 Open/Short/Load Calibration

Open/Short/Load calibration offers the highest accuracy over the widest frequency range and compensates more effects than the Thru calibration. A major disadvantage however is that not every test setup can be used to perform e.g. a Short calibration. This is especially the case if the DC portion of the signal cannot be removed during calibration.

The following figure shows the three states that must be measured to perform an Open/Short/Load calibration.
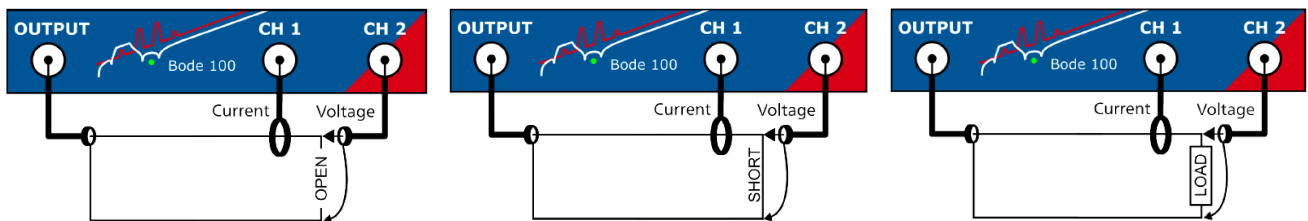

Figure 25: Open/Short/Load calibration in Voltage/Current measurement mode

4.7 Measurement Setup Verification

No matter if using a setup with or without calibration, it is always recommended to verify the measurement setup. To do so, a known DUT can be measured. Note that a DUT having a different impedance than the calibration element should be used for verification.

The following figure shows the measurement setup used for the experiment in chapter 3 on page 6 ff. In this case a 100 Ω resistor was measured to verify the setup. The measurement result shows a flat line at 100 Ω. Based on this measurement result no additional calibration was applied.
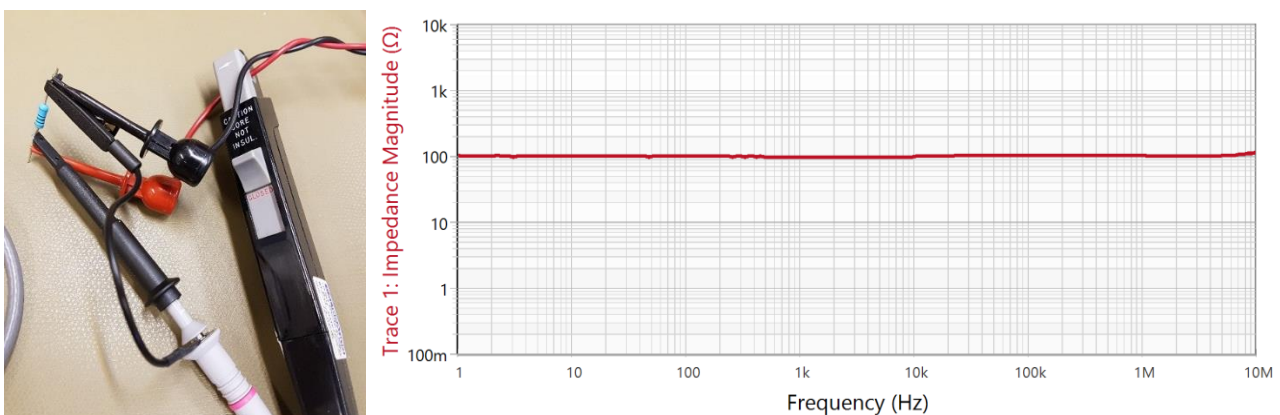

Figure 26: Verifying the measurement setup measuring a known impedance

Note: The DUT used for verification must be able to withstand the DC voltage that is applied during the test!

5 Summary

In the past, power supply stability analysis has been performed mainly in space applications [7], [8] that include complex DC power distribution systems with multiple regulators and different DC power bus levels.

Today complex power electronic systems are becoming widely spread in many application fields such as embedded system design and electric vehicle drive trains. To avoid stability problems in the field, stability should be considered during the development process of power electronic systems.

The input impedance of a DC/DC converter is a critical design parameter for stability. Measuring the input impedance is a simple possibility to either evaluate a black-box converter system or to prove simulation results. Converter input impedance and converter output impedance together with filter impedance are critical parameters that must be considered when connecting multiple regulators and filters to form a power distribution system. Improper impedance ratios can result in system instability.

Bode 100 in combination with the Bode Analyzer Suite offers an advanced platform for any power system impedance measurement. With the flexible hardware and software design, a high variety of test-setups are supported. The high noise rejection and dynamic range of the Bode 100 makes it the perfect choice for power system impedance measurements. Together with the Bode Analyzer Suite, Bode 100 is a powerful tool that should not be missing on a power electronic engineer's bench.

6 References

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