Application Note

Loop-Gain Reconstruction from Output Impedance for DC/DC Converters

Eduardo Rico, Moritz Müller

ABSTRACT

The loop-gain bode plot is essential for evaluating DC/DC converter stability and transient response. Traditional voltage-injection methods require breaking the feedback loop at an accessible node, which is increasingly impractical as modern integrated power converters eliminate external feedback access. This application note presents the output-impedance reconstruction method as an alternative for DC/DC converters without feedback access. By measuring open- and closed-loop output impedances using a vector network analyzer, the loop gain can be directly reconstructed without access to feedback nodes. The method is validated using the LM5126A-Q1 synchronous boost controller, demonstrating strong agreement with traditional voltage-injection measurements across various operating conditions. The approach is then applied to the LMG5126 integrated GaN boost converter, proving its necessity for highly integrated power solutions where traditional loop characterization is impossible.

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1 Introduction

The loop gain represents the product of all gains around the feedback loop of a regulating converter. The loop-gain transfer function $T(S)$ is determined by the elements of the control loop, the compensation network, the error amplifier, the PWM modulator, and the power stage of the converter. The loop-gain bode plot is commonly used as a tool to evaluate the stability of a converter and show the resilience of the power supply against load and supply voltage variations.

The traditional method to measure the loop-gain of the converter is the voltage-injection method. This method involves breaking the feedback loop at an appropriate point with an injection resistor and introducing a sinusoidal perturbation. The signal is then measured at both sides of the resistor, comparing the injected and attenuated signal across a wide frequency range.

To ensure valid measurements, an appropriate injection point must be chosen. At this point, the forward impedance Z_{fwd} must be much greater than the backward impedance Z_{bwd} ; this ensures the disturbance signal is distributed around the loop rather than being shunted. The feedback path is ideal for this reason: the feedback divider (typically kΩ) has much greater impedance than the converter output (mΩ range).

$$|Z_{fwd}| \gg |Z_{bwd}| \tag{1}$$

The measurement is also susceptible to non-linear behavior at certain signal levels, which can cause the crossover frequency to shift significantly. Therefore, it is crucial to monitor the effect of the signal level on the output of the converter in the range of interest.

Figure 1-1 shows the recommended voltage-injection measurement setup. The injection transformer delivers a sinusoidal perturbation across the injection resistor, which is placed between the output of the converter and the internal feedback divider. The probes of the vector network analyzer (VNA) are placed at each side of the injection resistor.

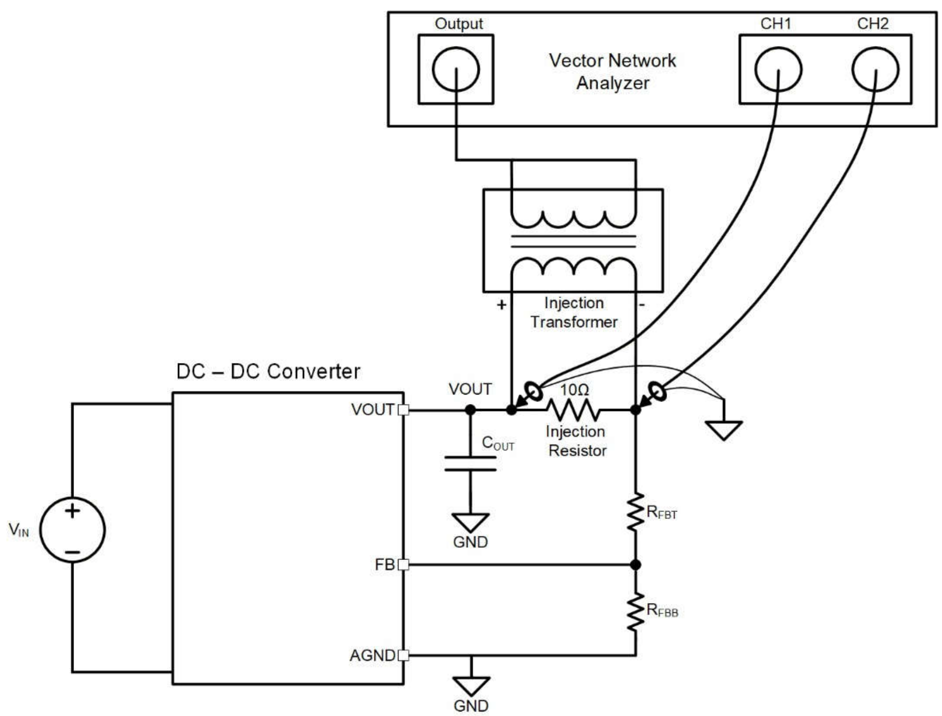

Figure 1-1. Voltage-Injection Measurement Setup

Overall, this method offers the fastest and most simple way to verify the stability of a power supply, especially for boards with built-in injection resistors and the necessary test pins. However, the voltage-injection method has significant limitations. First, the entire measurement must remain in a small signal response, where the device can react with duty cycle change and stays in the same mode. If the injection signal level is too high, non-linear behavior (large signal response) can shift the measured crossover frequency, leading to incorrect stability assessments. Second, the method provides limited insight into transient response beyond phase and gain margin calculations. Third and most critical, modern integrated power converters increasingly hide their feedback networks internally, making them inaccessible for loop-breaking measurements.

Given these limitations, particularly for converters with inaccessible feedback paths such as the LMG5126, an alternative measurement method is needed. The output-impedance reconstruction method addresses this issue by reconstructing loop gain from external impedance measurements alone, requiring no access to internal feedback nodes. This approach is applicable to both traditional controllers and modern integrated power modules, making it a universal characterization technique for power converters.

2 Theory and Background

The loop gain $T(S)$ can be derived from the open-loop impedance $Z_{OL}(S)$ and the closed-loop impedance $Z_{CL}(S)$. The open-loop impedance is determined by the power stage and is composed of passive components that form the topology, such as the inductor, input and output capacitors, FET resistances, and board parasitics. It is measured when all conversion switches are off. The closed-loop impedance is the output impedance measured when the control loop is actively regulating in steady state. Figure 2-1 visualizes the closed-loop system for a converter.

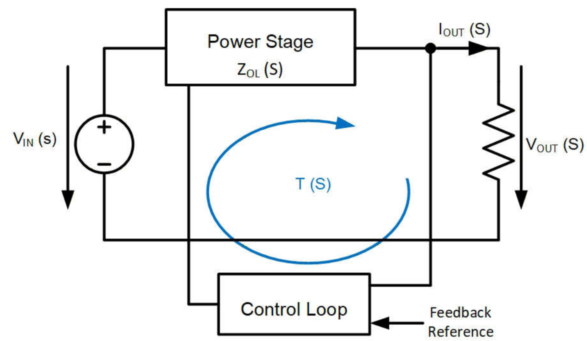

Figure 2-1. Converter Loop Gain

The loop gain and the output impedances are related by the following equation (refer to [8, Ch. 9.2.1]):

$$Z_{CL}(S) = \frac{Z_{OL}(S)}{1 + T(S)} \quad (2)$$

This equation reveals a fundamental design principle: closed-loop impedance is inversely proportional to loop gain. At frequencies below the crossover frequency where loop gain is high, the closed-loop impedance is significantly reduced by the feedback control. At higher frequencies where loop gain drops below 0 dB, the open-loop impedance becomes dominant and closed-loop impedance approaches $Z_{OL}(S)$. A critical design objective for any power supply is maintaining low output impedance across the frequency range to enable good load-transient response. Understanding the relationship between $T(S)$, $Z_{OL}(S)$, and $Z_{CL}(S)$ is essential to achieve this goal.

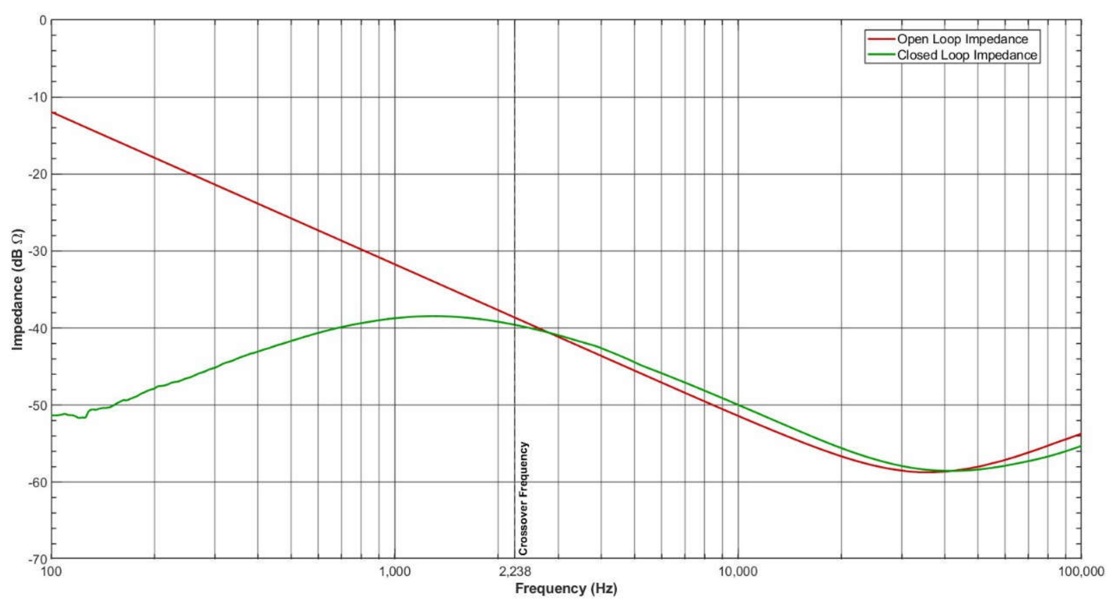

Figure 2-2. LM5126EVM Output Impedance: Open Loop vs. Closed Loop

By rearranging Equation 2 to solve for T(S), the loop gain can be derived as:

$$T(S) = \frac{Z_{OL}(S)}{Z_{CL}(S)} - 1 \quad (3)$$

This relationship is the foundation of the output-impedance reconstruction method. By measuring both the open- and closed-loop output impedances, the loop gain can be directly computed without requiring access to internal feedback nodes or breaking the control loop.

Calculating the loop-gain requires separating the real and imaginary components of the output impedances to compute the loop-gain magnitude and phase. Using the following formulas in a spreadsheet tool the measured data can be easily processed.

$$Z = \frac{|Z_{OL}|}{|Z_{CL}|} \quad (4)$$

$$\varphi = \varphi_{OL} - \varphi_{CL} \quad (5)$$

$$Re\{Z\} = Z \times \cos\varphi, \quad Im\{Z\} = Z \times \sin\varphi \quad (6)$$

$$|T(S)| = \sqrt{(Re\{Z\} - 1)^2 + (Im\{Z\})^2} \quad (7)$$

$$T(S)\ [dB] = 20 \times \log_{10}(|T(S)|) \quad (8)$$

$$\angle T(S)\ [°] = \tan^{-1}\left(\frac{Re\{Z\} - 1}{Im\{Z\}}\right) \quad (9)$$

3 Output-Impedance Measurement

The *Gain / Phase* setup of the VNA allows direct measurement of the output-impedance transfer function of the power supply. The output impedance is calculated by dividing the voltages measured at the two channels of the VNA, where channel 2 measures the output voltage of the converter and channel 1 measures the voltage at the injection node. Since this voltage appears across the known injection resistor R_{INJ} , it defines the injected current via Ohm's law ($I_{INJ} = (V_{CH1}/R_{INJ})$). The output impedance is therefore the voltage response V_{CH2} to this known current stimulus:

$$Z_{OUT}(S) = R_{INJ} * \frac{V_{CH2}}{V_{CH1}} \quad (10)$$

When computing the loop gain the effect of the injection resistor cancels out, as it appears both in the open- and closed-loop output impedance.

$$T(S) = \frac{R_{INJ} * \frac{V_{CH2,\ OL}}{V_{CH1,OL}}}{R_{INJ} * \frac{V_{CH2,CL}}{V_{CH1,CL}}} - 1 \quad (11)$$

The parasitic impedance of the injection leads and the channels of the VNA must be accounted for. A Thru calibration eliminates the effect of parasitic impedance from the leads. Essentially shifting the plane of measurement, from the ports of the VNA to the tip of the probes. The result after calibration should be a constant 0 dB gain and 0° phase across the frequency range. To perform the calibration, connect the channels directly to the output of the injection transformer as shown in figure 3-1.

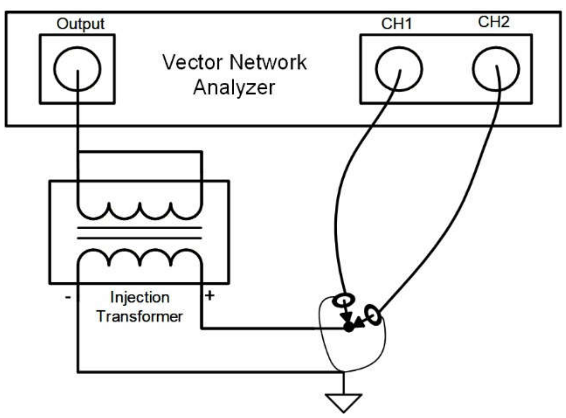

Figure 3-1. Thru Calibration

For accurate open-loop impedance measurement, a critical consideration is output-capacitor derating. Capacitors, especially ceramic, exhibit significant capacitance reduction with increasing bias voltage, which directly affects impedance. To ensure the open-loop measurement reflects the same capacitor characteristics as during closed-loop regulation, a DC bias voltage must be applied at the output capacitors equal to the nominal output voltage of the converter.

The bias supply is connected through a series diode to the output node. The diode serves two functions: it prevents reverse current from flowing back into the bias supply and ensures the impedance measurement sees only the capacitor impedance without the bias supply acting as a parallel impedance path.

4 Method Comparison on LM5126EVM

The LM5126A-Q1 synchronous boost controller evaluation board (see [3]) served as the perfect setup to compare the traditional voltage-injection method and the output impedance method to obtain the loop-gain bode plot. The board has an injection resistor between the V_{OUT} sense pin of the controller and the internal feedback divider, as well as the necessary test points, enabling both traditional voltage-injection and output-impedance measurements on the same board.

To validate the accuracy of the output-impedance reconstruction method, the loop gain obtained from the voltage-injection and output-impedance reconstruction method were compared across compared across 72 configurations. These configurations were generated by testing all possible combinations of the four parameter sets shown in table 4-1: four compensation setups, three input voltages, three output currents, and two output-capacitance values.

Table 4-1. LM5126EVM Configuration Parameters

Compensation	V_{IN}	I_{OUT}	C_{OUT}
1. $R_{COMP} = 10k\Omega, C_{COMP} = 61nF, C_{HF} = 84pF$	9V	0.2A	350 μF
2. $R_{COMP} = 20k\Omega, C_{COMP} = 15nF, C_{HF} = 500pF$	13.5V	1.15A	650 μF
3. $R_{COMP} = 30k\Omega, C_{COMP} = 5.6nF, C_{HF} = 100pF$	18V	2.5A	
4. $R_{COMP} = 40k\Omega, C_{COMP} = 15nF, C_{HF} = 100pF$			

The methods showed strong agreement across the tested configurations. The best consensus occurred with compensation setup 1 and low output capacitance, yielding a crossover frequency and phase margin deviation of only 3.11% and 8.07% respectively across the line voltage and load ranges. For compensation setup 4 with high output capacitance, the average error increased to 15.14% for crossover frequency and 8.16% for phase margin.

All configurations showed a significant drop in accuracy beyond the crossover frequency, typically around 20 kHz. This discrepancy highlights a fundamental limitation of the output-impedance reconstruction method: as the output impedance rises due to parasitic inductance in the output-capacitor bank and the open-loop impedance becomes dominant at high frequency, Z_{CL} and Z_{OL} converge in magnitude. This convergence makes the calculation highly sensitive to small measurement errors. In boost topologies, the Right-Half-Plane Zero limits the crossover frequency, causing these magnitudes to converge at lower frequencies than in other topologies, making this discrepancy more evident. Despite this high-frequency limitation, the reconstruction remains accurate across the bandwidth of interest.

The components of the injection network, along with the connections between the output-capacitor bank, the injection network and the probes, introduce parasitic impedance. These parasitics cause measurement errors at high frequencies as inductance increases. Because the reconstruction becomes increasingly sensitive to error at higher frequencies, minimizing these parasitics is essential to extending the accuracy range.

The following figures show a comparison of the methods for compensation setup 2 with high output capacitance on the LM5126 evaluation board, $V_{in} = 13.5V$, and $I_{out} = 1.15A$. Figure 4-1 displays the loop gain measured using the traditional voltage-injection method, while Figure 4-2 shows the same converter measured using the output-impedance reconstruction method.

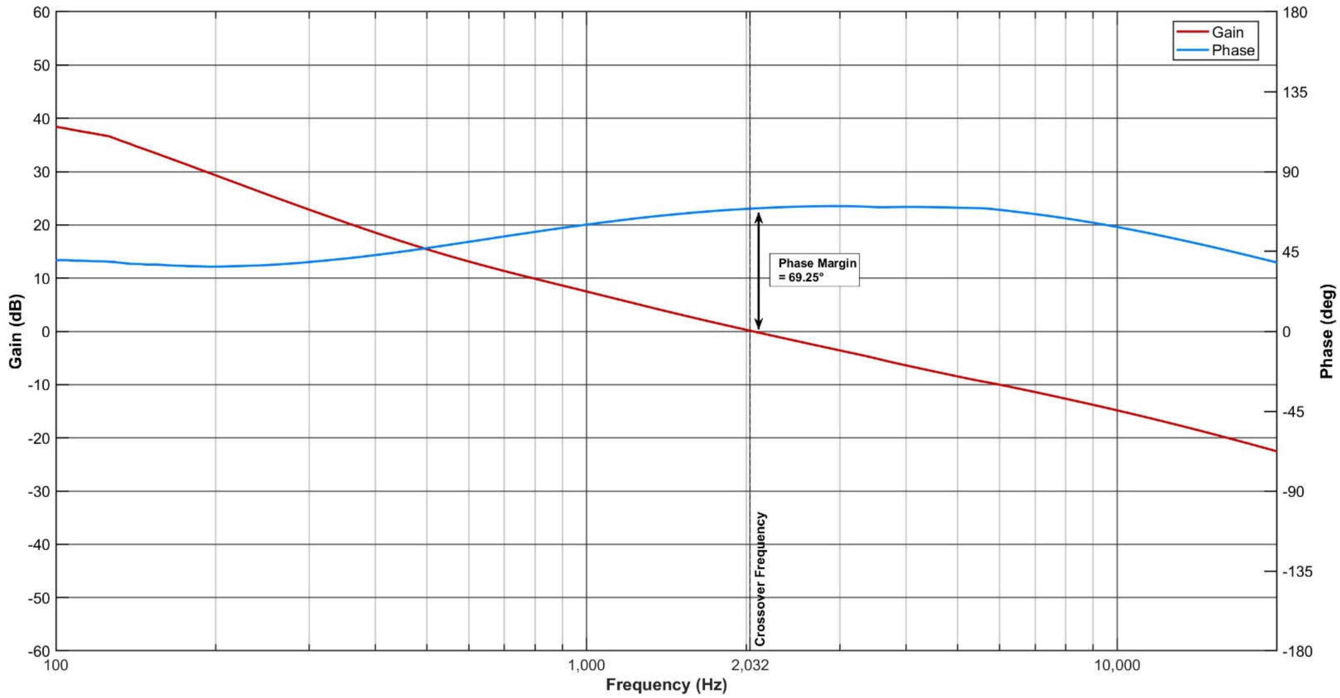

Figure 4-1. Voltage-Injection Method LM5126EVM

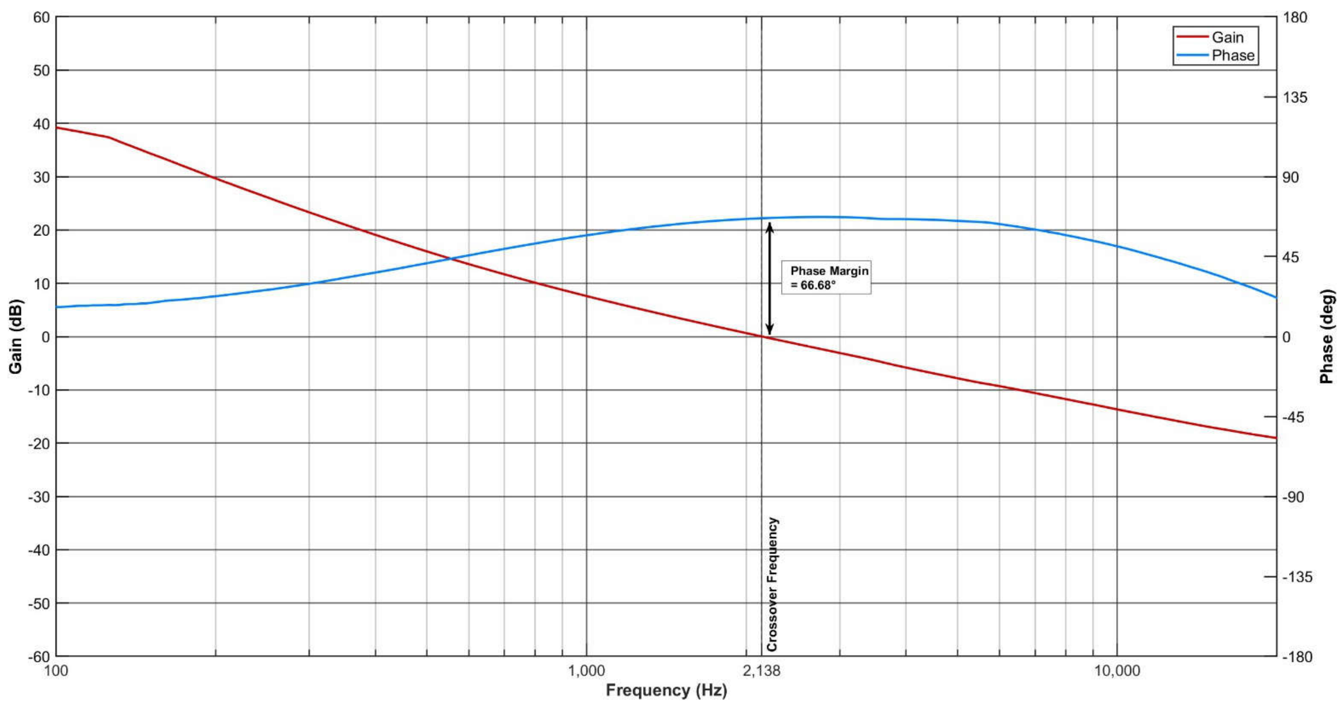

Figure 4-2. Output-Impedance Reconstruction LM5126EVM

For this configuration, the crossover frequency and phase margin deviation between the methods is 5.21% and 3.71% respectively, well within an acceptable tolerance.

5 Application for the LMG5126

The LMG5126 is a synchronous boost converter that integrates GaN switches, gate drivers, and control logic on a single chip. This integration provides several advantages, including a compact footprint, minimized parasitic inductance, and improved noise immunity. In the LMG5126, the feedback network, error amplifier, and compensation nodes are all internal with no external access. Consequently, traditional voltage-injection loop-gain measurements, which require breaking the feedback loop, cannot be used. The output-impedance reconstruction method addresses this limitation by characterizing the loop using only external measurement points.

The LMG5126EVM (see [2]) is used to evaluate the integrated converter. The injection network and bias supply are added as follows:

1. Solder the injection resistor to the ground pin of the converter. Its value does not affect the loop-gain calculation, since it cancels out in the ratio (see Section 3); standard values are 10Ω and 50Ω, and in this measurement a 10Ω injection resistor is used (WR506170A1009GGP00).
2. Add an injection capacitor in series with the injection resistor to block DC and prevent the converter output from shorting to ground. Choose a capacitance value that presents low impedance at the lowest frequency of interest; too high an impedance attenuates the injected signal and increases noise at low frequency. A 22µF capacitor (EEH-ZA1K220P) is chosen.
3. Build the bias supply from a diode (1N002) and a current-limiting resistor connected in series at the converter output. Adjust depending on power level.

Solder the injection network as close as possible to the pins of the output-capacitor bank, and connect the VNA channels directly to those same pins. This minimizes the parasitic impedance included in the measurement, extending the range and improving the accuracy of the reconstructed bode plot.

The closed-loop measurement is suceptible to noise especially at low frequencies. Tune the injection-signal level and receiver bandwidth of the VNA to minimize noise. Multiple iterations are needed to find the optimal conditions. Phase margin may deviate slightly dependent on signal level.

Figure 5-1 displays the measurement setup.

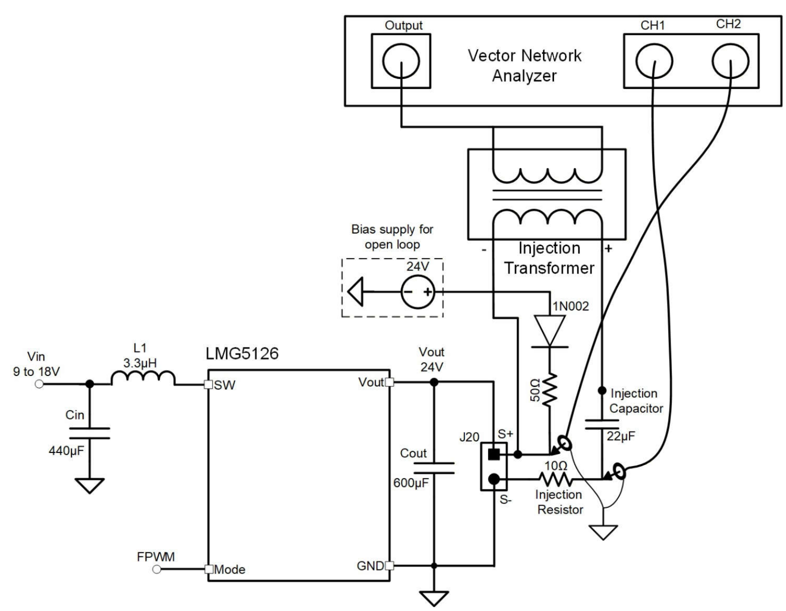

Figure 5-1. LMG5126EVM Output-Impedance Measurement Setup

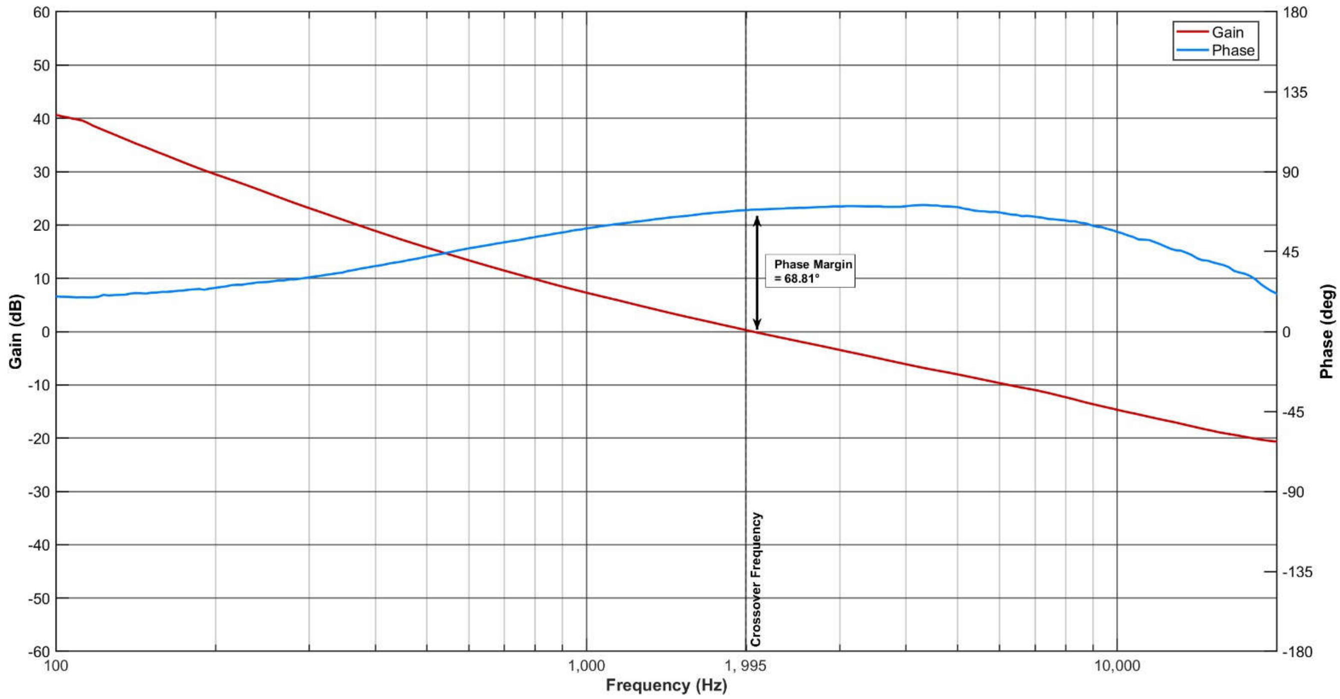

Figure 5-2. Output-Impedance Reconstruction LMG5126EVM

As shown in Figure 5-2, this approach successfully produces a complete loop-gain bode plot, providing the necessary data to evaluate the stability of the converter.

6 Summary

This application note validates the use of output-impedance reconstruction as a robust alternative to traditional voltage-injection for loop-gain measurement. The test on the LM5126A-Q1 demonstrated that the method provides highly accurate crossover frequency and phase margin data. Although accuracy is limited at higher frequencies, the method remains effective within the bandwidth of interest. Crucially, this approach enables the stability characterization of converters, where the internal feedback path is inaccessible, such as the LMG5126.

7 References

1. Loop-gain reconstruction from output impedance tool
2. Texas Instruments, *LMG5126-Q1 Boost Converter Evaluation Module User's Guide (Rev. B)*, user's guide.
3. Texas Instruments, *LM5126AEVM-BST EVM Users Guide*, user's guide.
4. Texas Instruments, *Loop Gain Reconstruction of a Step-Down Converter from Output Impedance*, application note.
5. OMICRON Lab, 2020. Application Note. Output Impedance for Stability Analysis
6. OMICRON Lab, 2018. DC/DC Converter Stability Measurement
7. *Output Impedance Measurements and Loop Gains*, webpage.
8. R. W. Erickson, Fundamentals of Power Electronics, 1996.