2-Port Impedance Measurement using the P2102A Probe and ZNL6 VNA

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High speed Printed Circuit Board (PCB) design requires well designed Power Delivery Networks (PDN) to support today's FPGAs and custom mixed-signal ASICs. The PDN contains important impedance information that can tell a designer how a system will react to dynamic currents and the impact of PCB layout. If we consider the PDN as a transmission line between the Voltage Regulator Module (VRM) and the load (ASICs), then a starting point for a good PDN design is the VRM.

Today VRMs need to supply power to multiple VDD cores to support FPGAs and/or custom ASICs using multi-gigabit ethernet, PCIe, and DDR memory interfaces. With that being said, vendor information for a VRM's output impedance is not available and not always accurate when it is supplied. Further, measuring ultra-low impedance on multiple VRMs or multi-topology DC-DC regulators is a challenge for any design engineer.

The 2-port shunt-through impedance measurement is the gold standard for measuring a VRM's output impedance in the microOhm and milliOhm region [1]. However, it is not always possible to make these measurements with direct coaxial connectors designed into the PCB or Device Under Test (DUT). Therefore, when a designer makes these types of measurements with a Vector Network Analyzer (VNA), the method of connecting the DUT requires attention to detail to ensure inductance and various error sources are minimized to allow an accurate measurement. To get the most out of your VNA, you need to use the right probes and accessories to ensure your particular measurement application is successful. With a browser probe like the P2102A you can quickly characterize multiple VRMs to ensure stability or even check if your model is accurate during your initial PDN design.

The Picotest P2102A 2-port PDN transmission line probe is a browser probe that achieves a very low inductance at the tip to mitigate space constraints on a dense PCB, while eliminating the need to solder COAX, add additional coaxial connectors, or other test points necessary for impedance measurements. It is especially useful when there are dozens of rails to assess and there isn't time, or PCB iterations available to provide test point implementations for each. Repeated measurements are simplified because connection is by simply touching the tip to an existing output capacitor pad. This browser probe comes with 4 probe tips to allow measurement across a variety of SMD packages on a PCB such as 1206, 0805, 0603, or 0402. The P2102A probe tips are available with 1X, 2X, 5X, and 10X attenuations. This allows flexibility for users to measure across a wide range of voltages. For instance, the 2X probe can measure 6Vrms without DC blocks. The tradeoff is the attenuation increases the impedance floor. In short, this 2-port P2102A probe is best suited for VRM, power plane, and decoupling measurements. An added benefit is that you can use Non-Invasive Stability Measurement (NISM) to assess power supply's stability at the same time as you assess the PDN [2].

The goal of this document is to show design and test engineers the process of how to set up and use the ZNL VNA with the Picotest P2102A browser probe to accurately measure the impedance of any VRM or power rail efficiently and quickly. This will also show you how to use this browser probe as a quick GO/NO-GO tester. In this application note, two DUTs will be measured as detailed by the process shown in Figure 1.

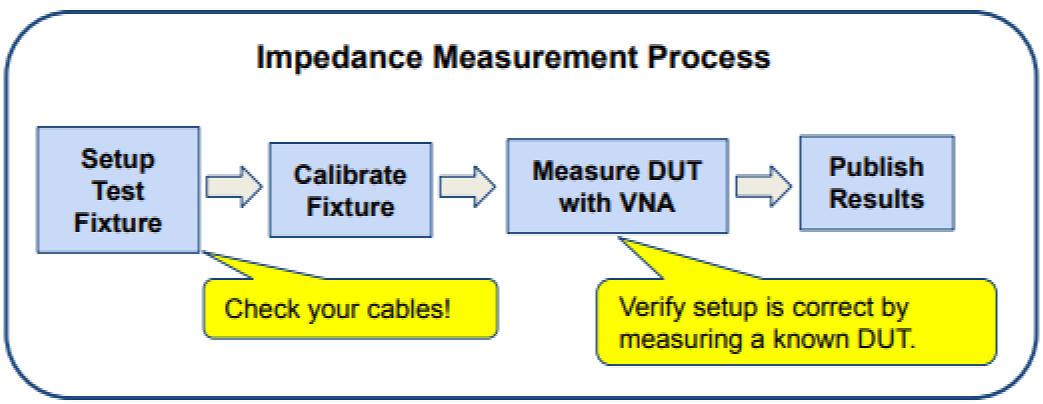

Fig. 1 - Impedance Measurement Process.

1.0 Test Equipment List

Description	Model	QTY
Vector Network Analyzer	Rohde & Schwarz ZNL6 [3]	1
2-port PDN Transmission Line Probe Kit	Picotest P2102A-2X [4]	1
Common Mode Transformer	Picotest J2102B-N [5]	1
Picotest PDN Cable®, BNC-BNC, 0.25 meter	BNCJ/BNCJ-250 [6]	1
SMA Female to N Male Adapter	Pasternack PE9081 [7]	2
BNC Female to N Male Adapter	Pasternack PE9002 [8]	2
3D Probe Positioner	Rohde & Schwarz RT-ZAP [9]	1
VRM Demo Boards (Flat and Varying Impedance)	LM20143B [10]	1
VRM - Infineon PS5401 Eval (DUT)	EVAL_PS5401-INT [11]	1
DC Power Supply and Electronic Load	Rohde & Schwarz NGL202 [12]	
Calibration Board/Substrate	Included in Picotest P2102A kit	1

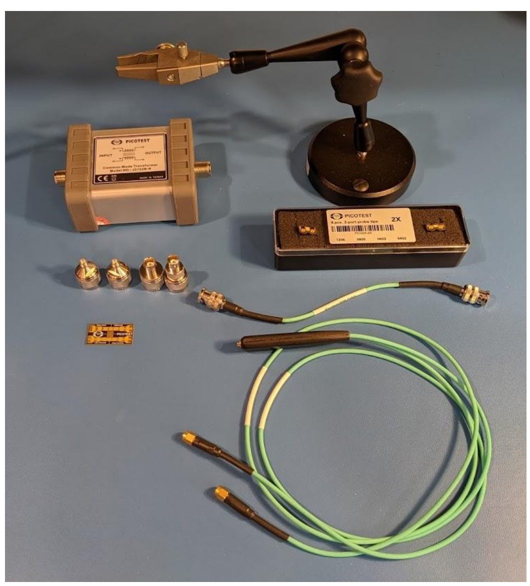

Fig. 2 - Picotest PDN cables, J2102B ground isolator, calibration substrate, P2102A probe, P2102A probe tips, and probe holder for measurement.

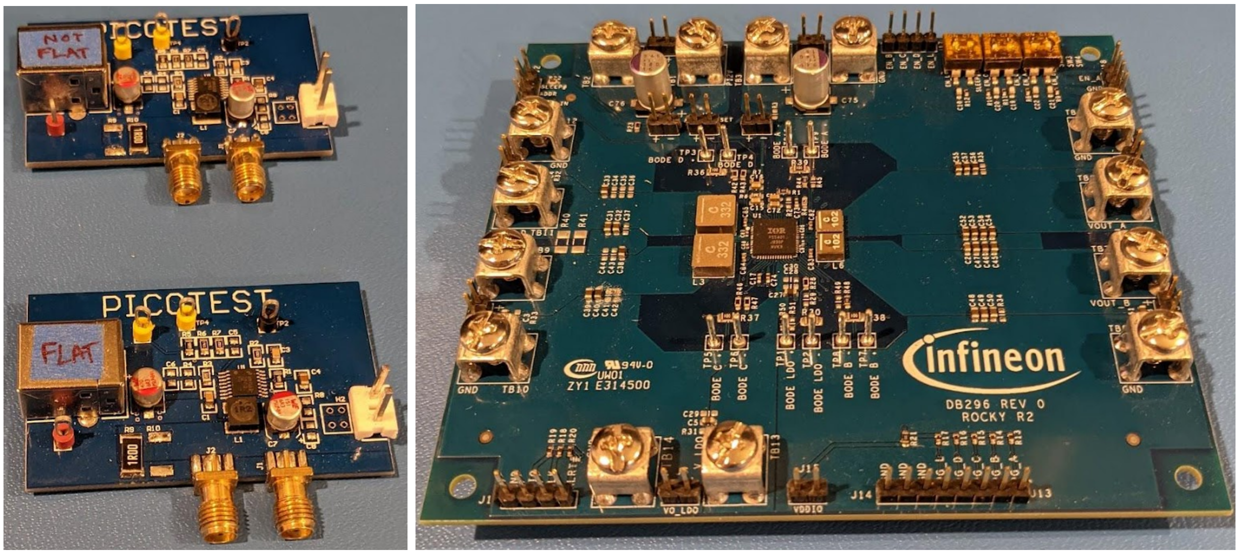

Fig. 3 - Picotest LM20143 DUTs (left) and Infineon PS5401 Eval DUT (right).

Note: The Picotest LM20143 test board may be referred to as Flat DUT and Not Flat (NF) DUT throughout this document.

2.0 Measurement Setup

The P2102A-2X probe tips includes 50 Ω series resistors (Rs), which can be set up/accounted for in the ZNL6 Offset Embed menu. Figures 4 and 5 provide a depiction of how the DUT is connected to the 2-port P2102A probe with the ZNL6.

For the other P2102A-#X probe tip models, set Rs as defined below in the ZNL series VNAs:
P2102A-1X - Rs = 0Ω
P2102A-5X - Rs = 200Ω
P2102A-10X - Rs = 450Ω

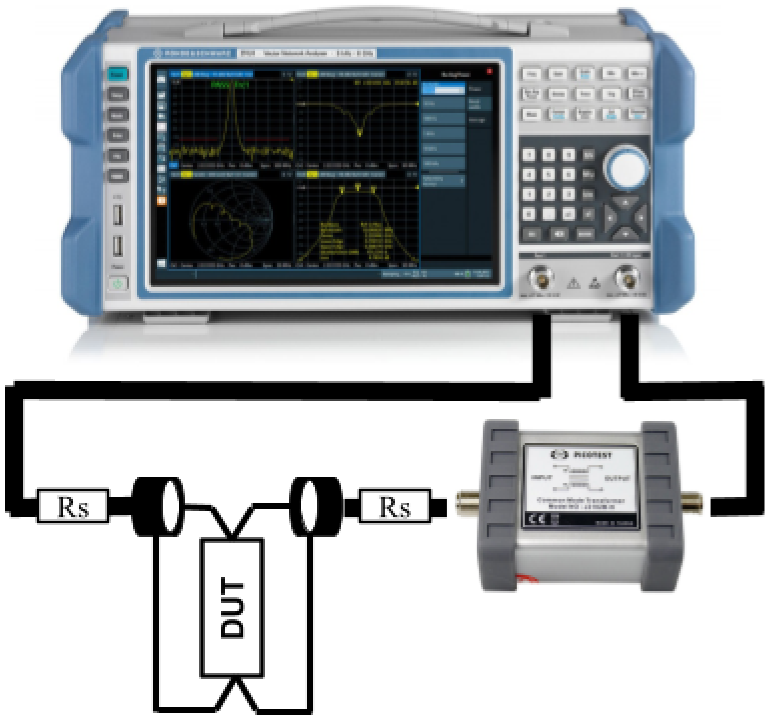

Fig. 4 - 2-port Shunt-Thru with series resistance impedance measurement setup using ZNL and Picotest ground isolator J2102B.

Many 2-port probe users already own a microprobe station, however, the commitment to setting up the camera, microscope, calibration, etc. is a much bigger commitment then sometimes necessary for simple VRM impedance or even stability measurements. This is where the P2102A browser probe provides a great option on-the-go, as depicted by Figure 5.

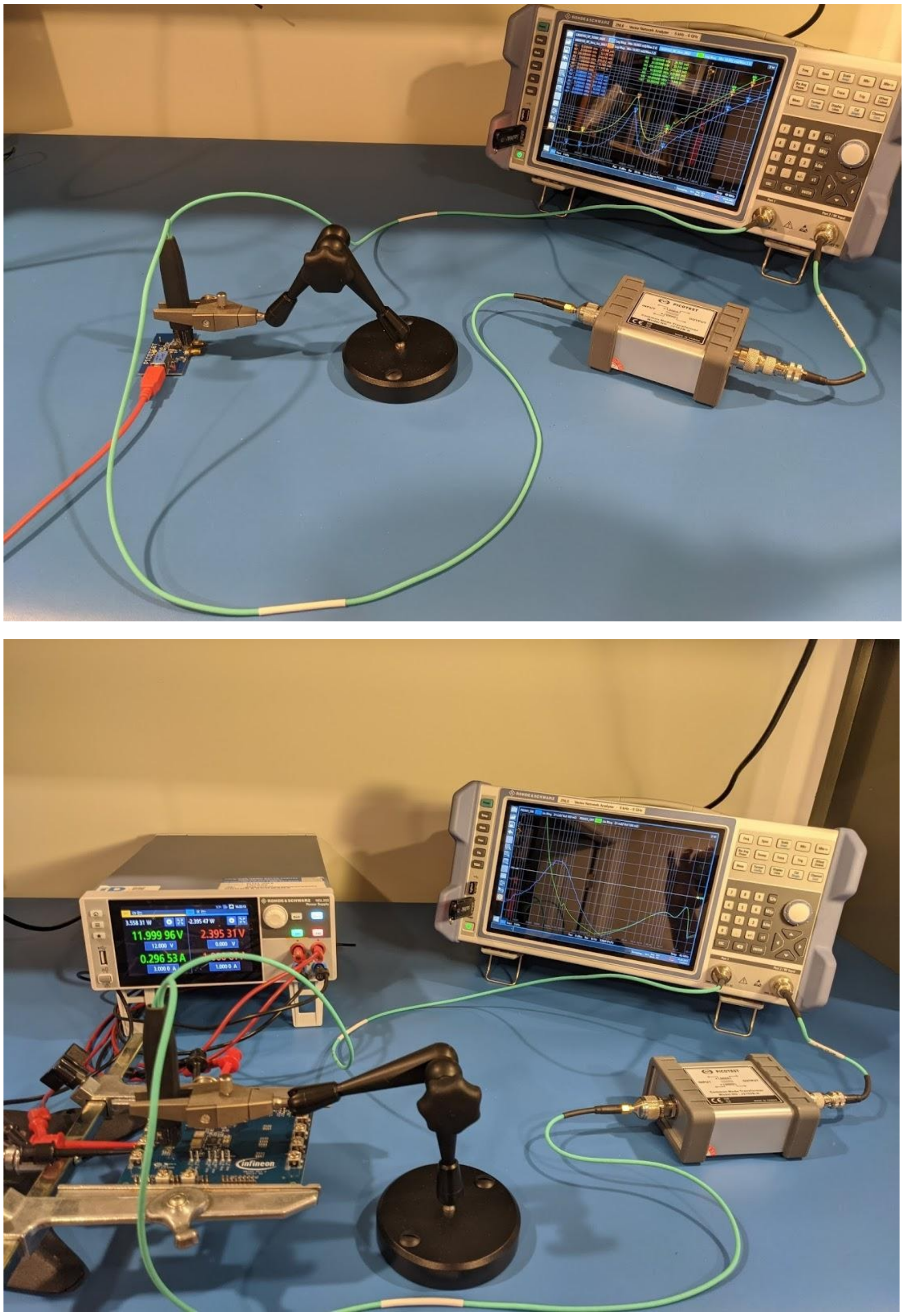

Fig. 5 - Measurement Setup after Calibration with DUTs.

The shunt-thru configuration inherently suffers a ground-loop error at low frequencies. The current flowing through the cable shield of the connection to channel 2 ground introduces a measurement error that can become significant at frequencies below a few MHz when measuring very low impedance values. To reduce the ground loop error at low frequencies, use a ground isolator or common-mode transformer (e.g., J2102B) or an active isolation device such as the J2113A [13].

Prior to making any measurements you should ensure calibration of the setup is performed by using the proper calibration method. The ZNL series VNA has multiple calibration options shown in Table 9-7 of the ZNL user manual. Proper calibration is critical since it corrects for contact resistance, tip inductance, coupling, and thermocouple effects. Picotest's recommendation is to use the Through - Open - Short - Match (TOSM) calibration method with the ZNL. This ensures high accuracy with a 12-term error correction model by requiring seven standard measurements shown by Figure 12. An example of why this is important is shown later in this document. In addition, to ensure consistent contact resistance, optimum accuracy as well as repeatability, a probe holder can be used during calibration and measurement. There are other calibration options available on the ZNL such as Transmission Normalization (Trans Norm) which is a through calibration method that has the option to include an isolation error calibration component.

Figures 6 and 7 provide a depiction of the probe tip location on each DUT. For Figure 6, an 0603 capacitor (C42) was removed prior to measurement and the 0603 probe tip is then used as shown. However, it is not necessary to remove the capacitor to make this measurement. For identification purposes, the probe head side with a label indicates the positive signal side.

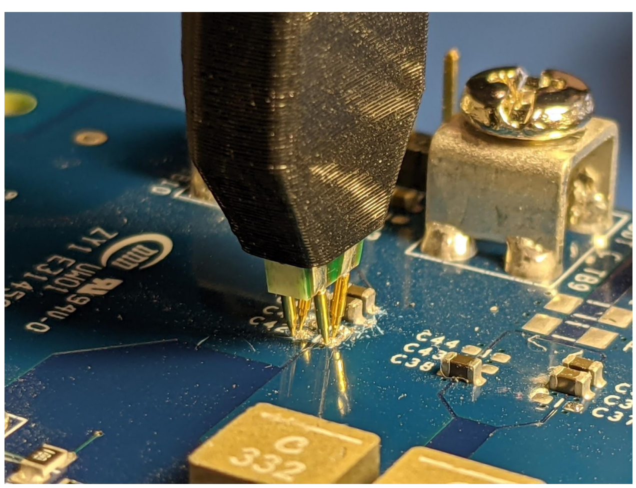

Fig. 6 - Probe location on DUT - Infineon PS5401 Eval at C42.

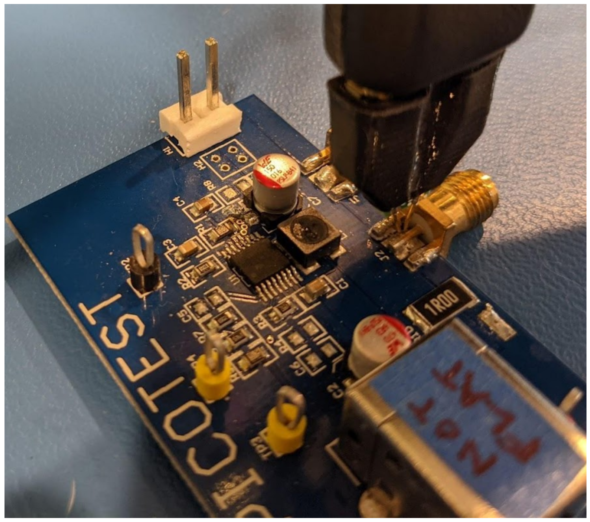

Fig. 7 - Probe location on DUT - LM20143 at J2.

3.0 Measurement Results

The results shown in Figure 8 depict the LM20143 DUTs both ON and OFF using the P2102A browser probe.

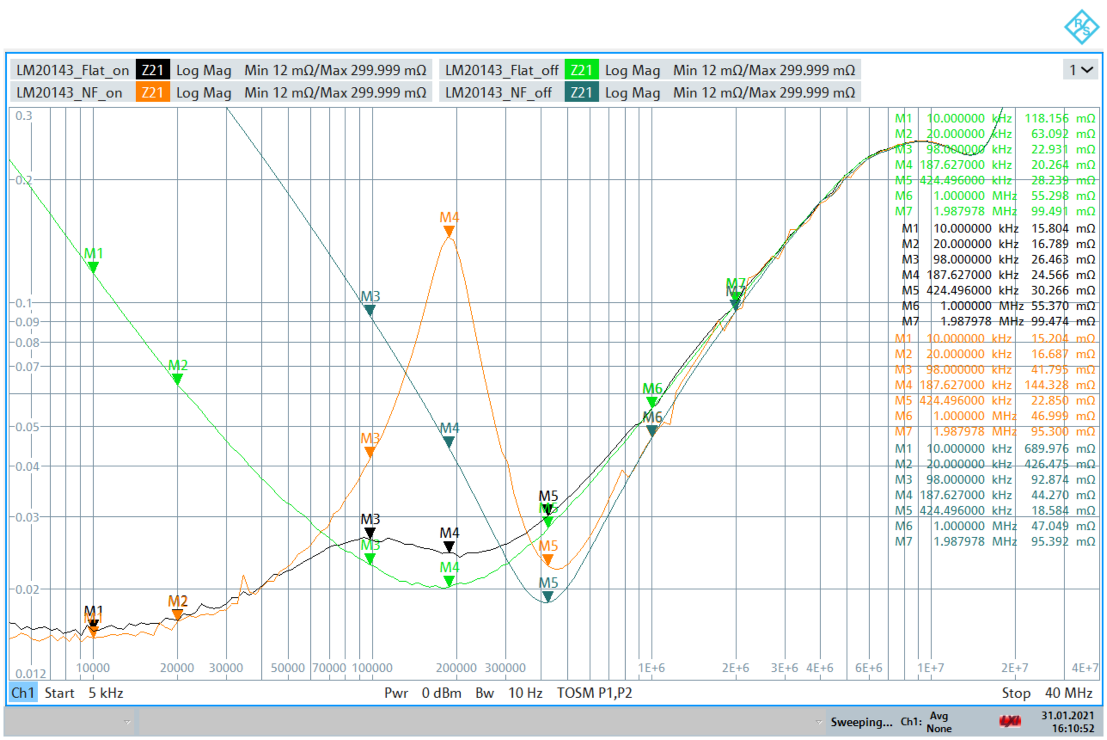

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Fig. 8 - LM20143 VRM Output Impedance results OFF and ON (TOSM calibration method).

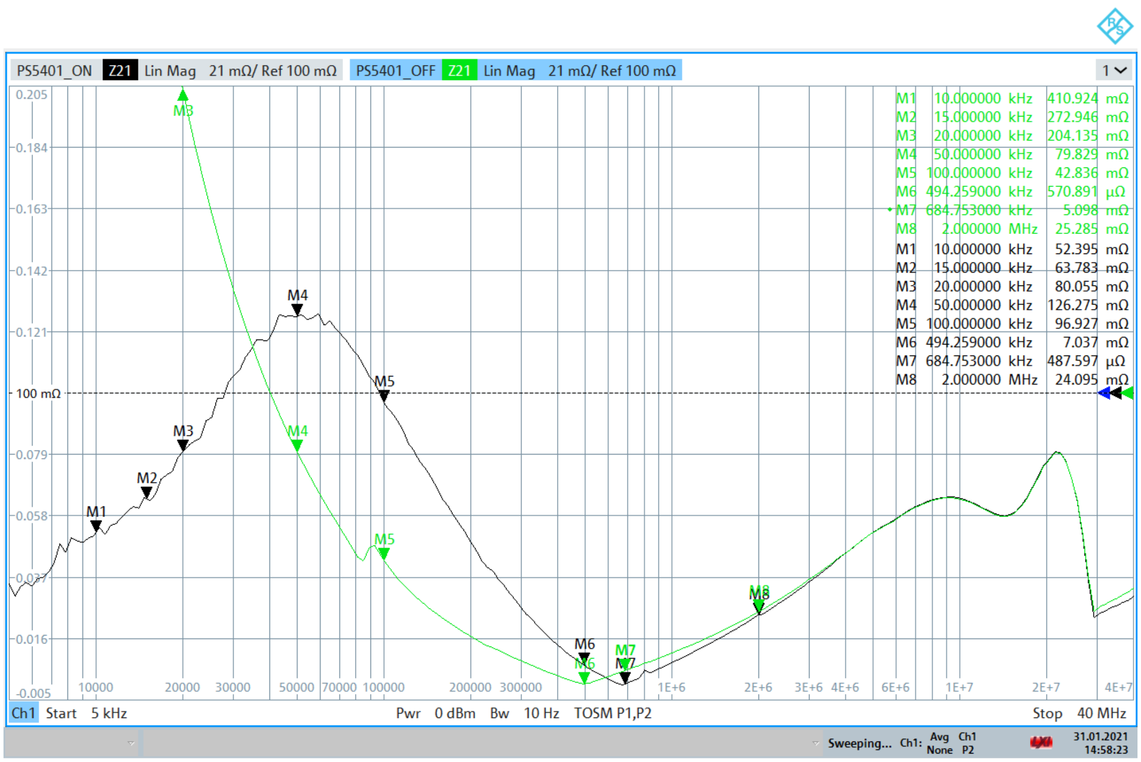

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Fig. 9 - Infineon PS5401 Eval - VRM Output Impedance Results OFF and ON at C42 (TOSM calibration method).

As shown by the results in Figure 9, it is possible to accurately measure below 10 mΩ with the P2102A browser probe.

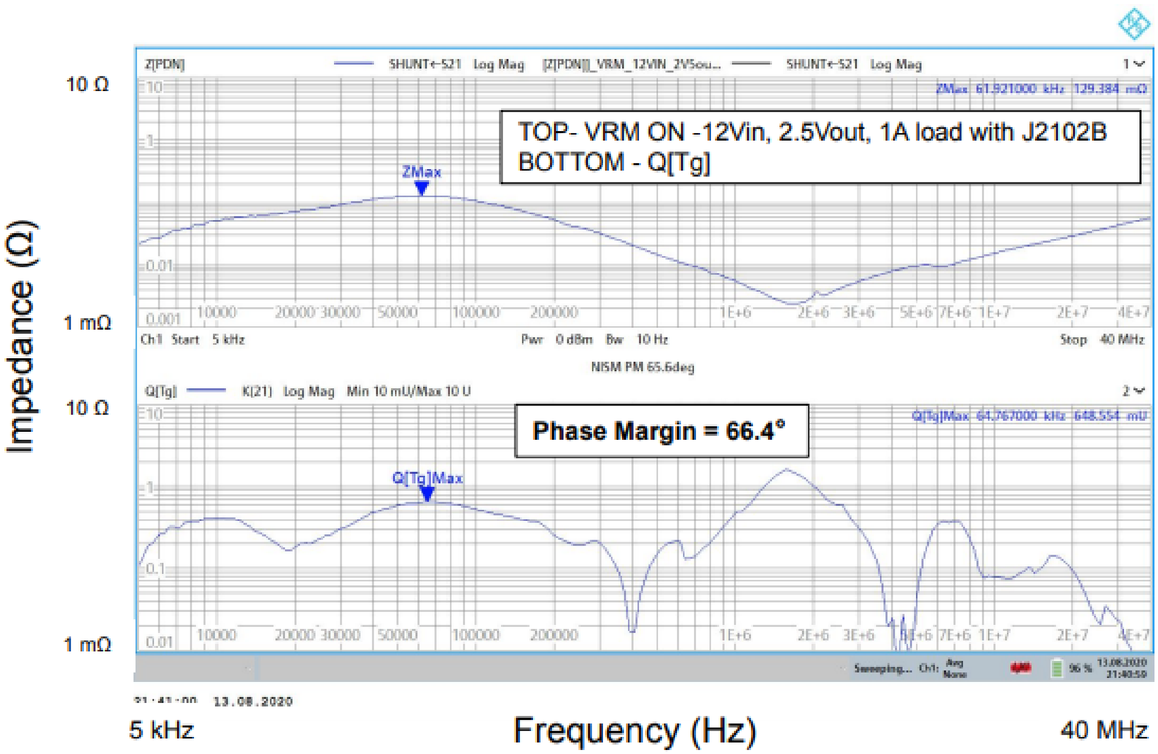

Fig. 10 - Infineon PS5401 Eval - VRM Output Impedance NISM Method on ZNL.

Using Picotest's optional NISM software for ZNL6, the impedance measurement can be used to directly determine the Stability Margin and equivalent Phase Margin without having to open the control loop. This can be a huge timesaver for systems with many VRM's, allowing the stability of each VRM to be quickly assessed using a browser probe. An example of NISM for the ZNL6 is shown in Figure 10, reporting 66.4° for the Infineon PS5401 VRM, indicating a stable control loop.

4.0 P2102A Calibration Checklist with ZNL

Calibration of Testing Setup for Shunt-Through Impedance with Series Resistance Measurement

After powering on the ZNL, with cables connected for calibration as shown in Figure 5, follow the steps below to calibrate your measurement setup prior to making measurements on your DUT.

4.1 De-embedding Probe with ZNL

Step 1: Press > **Offset Embed** button
Step 2: Select > **Single Ended**
Step 3: Under Port 1 Select > **Shunt L, Serial L** network as shown by Figure 11
Step 4: Set L1 = 0, R1 = 50Ω, L2 = 0, R2 = 10MΩ.
Note: 10MΩ, is the maximum value that can be set on the ZNL.

Step 5: Under Port 2 Select > **Shunt L, Serial L** network
Step 6: Set L1 = 0, R1 = 50Ω, L2 = 0, R2 = 10MΩ.
Step 7: Ensure 'Active' is checked

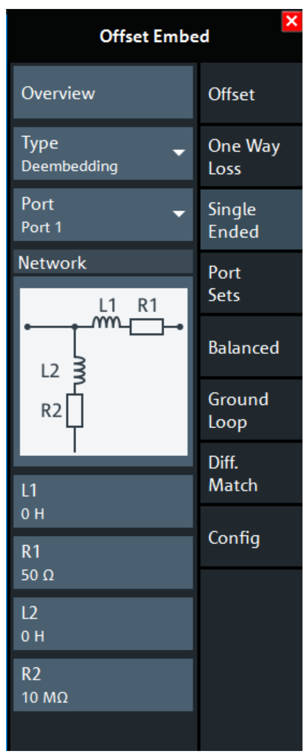

Fig. 11 - Offset Embed Menu - Shunt L, Serial L selection.

4.2 TOSM Calibration Method with ZNL

Step 1: (On the ZNL6) Press > **Freq** button - *Set desired span and Power (dBm)*
Step 2: Press > **Bw Avg Power** button
Step 3: Select LSK > **Bandwidth** then *select desired Bandwidth for sweep*
Step 4: Press > **Sweep** button then *set the desired Number of Points*

*Note: The lower the bandwidth ⇒ higher resolution but also the slower the calibration**

Step 5: Press > **Cal** button
Step 6: Select > **Start Manual**
Step 7: *Ensure both Ports 1 & 2* are ‘selected’
Step 8: Select > **TOSM**
Step 9: (As applicable) *Verify correct connectors, gender, and/or cal kit are selected for each Port*
Step 10: Select > **▶Start**
Step 11: Select Open then Select > **▶Start Cal Sweep**
Step 12: Repeat for all 7 calibration steps until ‘GREEN’ check marks are reflected as shown in Figure 13. Reference Figure 12 during each TOSM calibration step.
Step 13: Select > **✓ Apply**

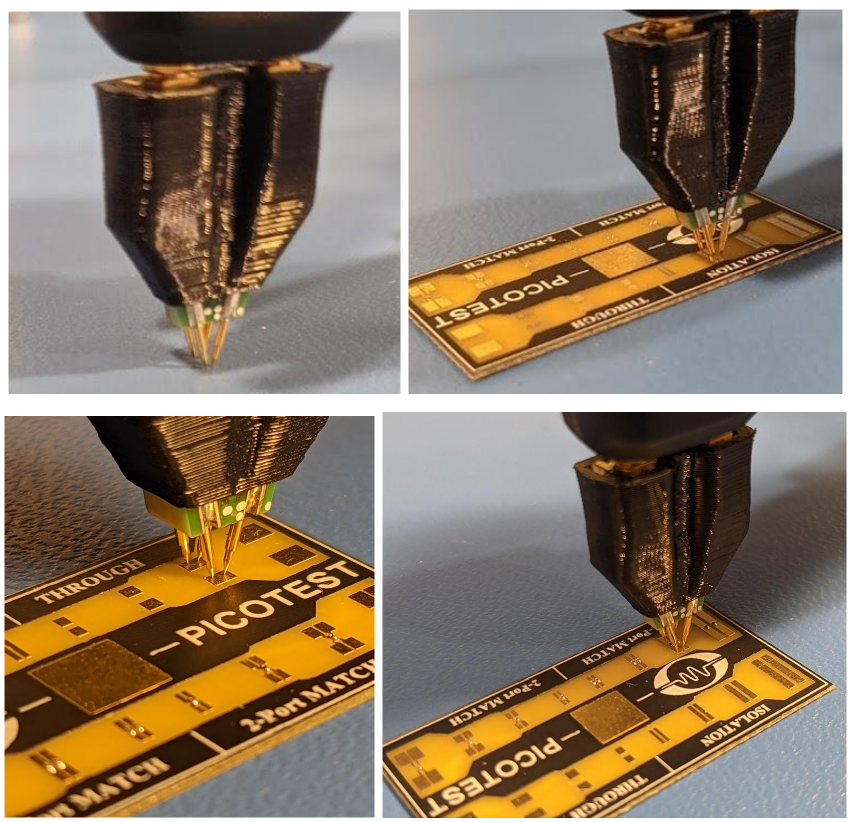

Fig. 12 - P2102A 2-port Calibration Open (top left), Short and Isolation (top right), through (bottom left) and Match/Load (bottom right) with ZNL6.

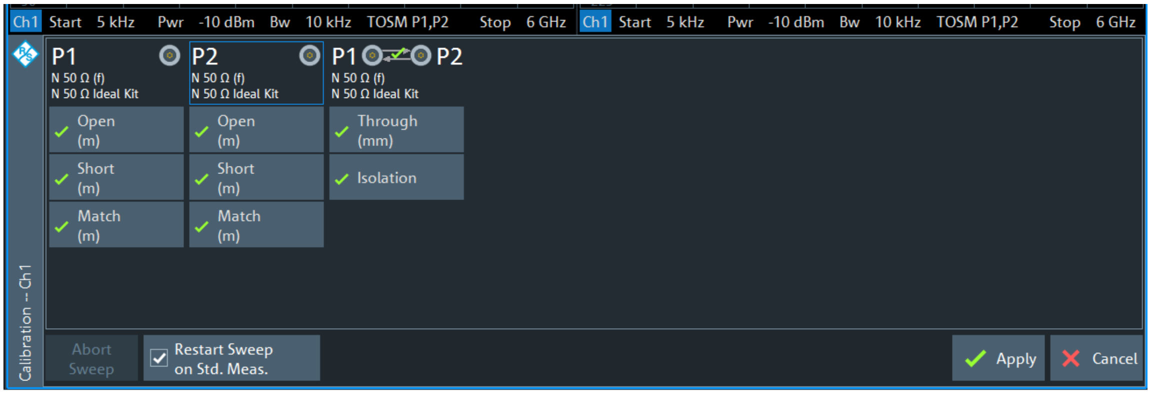

Fig. 13 - TOSM Calibration Steps Completed.

4.3 Checklist for Shunt-Through Measurement of the DUT

With the DUT connected to the ZNL6 to make a shunt-through measurement….

Step 1: (On the ZNL6) Press > **Freq** button - *Set desired span and Power (dBm)*
Step 2: Press > **Bw Avg Power** button
Step 3: Select LSK > **Bandwidth** then *select desired Bandwidth for sweep*

*Note: The lower the bandwidth ⇒ higher resolution but also the slower the measurement**

Step 4: Press > **Sweep** button
Step 5: Select LSK > **Sweep Type** then Select > **Log Freq** radio button
Step 6: Press > **Meas** button
Step 7: Select LSK > **Z ← Sij** then Select > **Z ← S21**
Step 8: Select > **Y- Z- Params** then Select > **Z21**
Step 9: Press > **Format** button then Select > **Lin Mag** radio button
Step 10: Press > **Cal** button then ensure '**User Cal Active**' box is '**checked**'
Step 11: Press > **Scale** button *if needed* Select > '**Auto Scale Diagram**' or '**Continuous Auto Scale Trace**' checkbox

Begin capturing measurements of the DUT…

Measurement accuracy can be further improved by instead using the TOSM calibration method versus the TRANS NORM method or even the TRANS NORM with isolation error calibration method. The TRANS NORM method does not account for inductive coupling errors. Figures 14 and 15 provide two examples comparing the measurement error due to inductive coupling when using the TOSM-calibration method versus TRANS NORM method. Figure 14 also shows a comparison with the TRANS NORM with an additional isolation error calibration component.

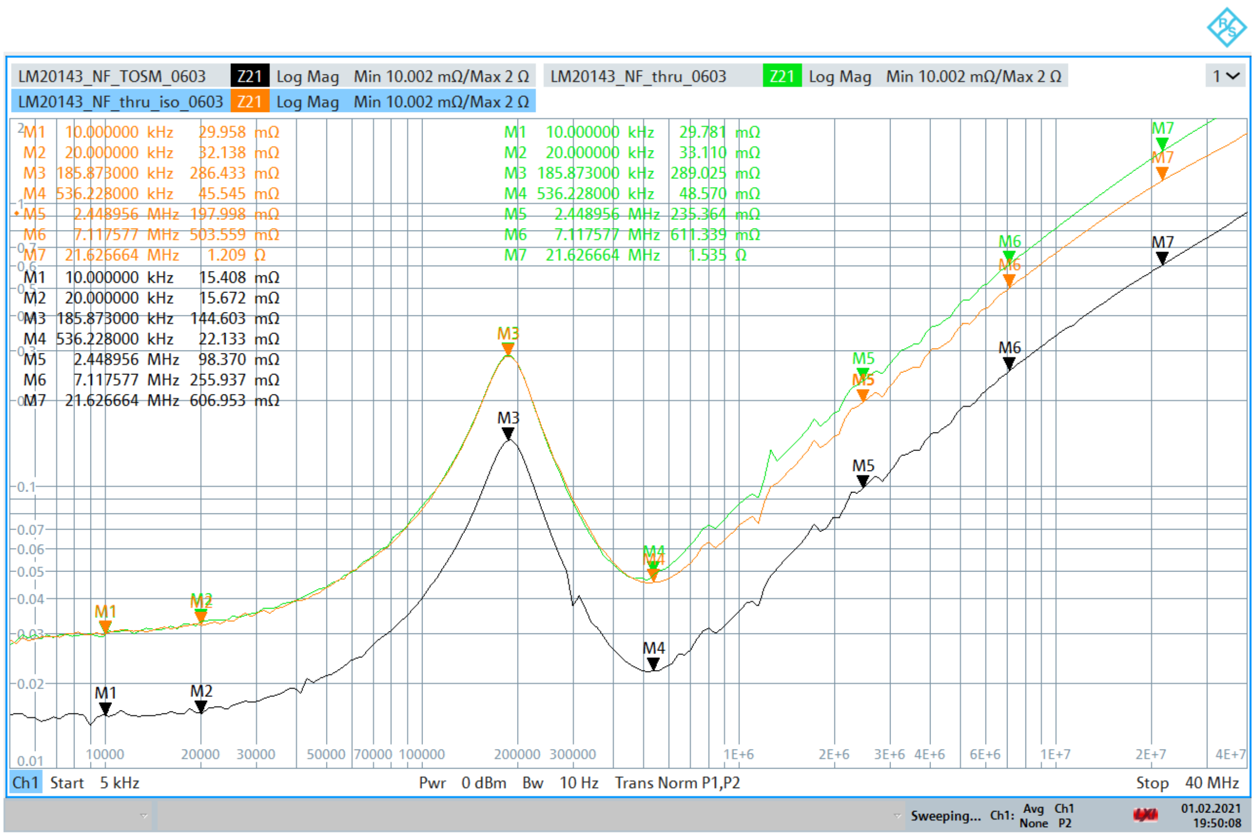

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Fig. 14 - LM20143 Not Flat- Measurement Results using TRANS NORM (green) vs. TRANS NORM with ISOLATION method (orange) vs. TOSM method (black) with ZNL6 and P2102A.

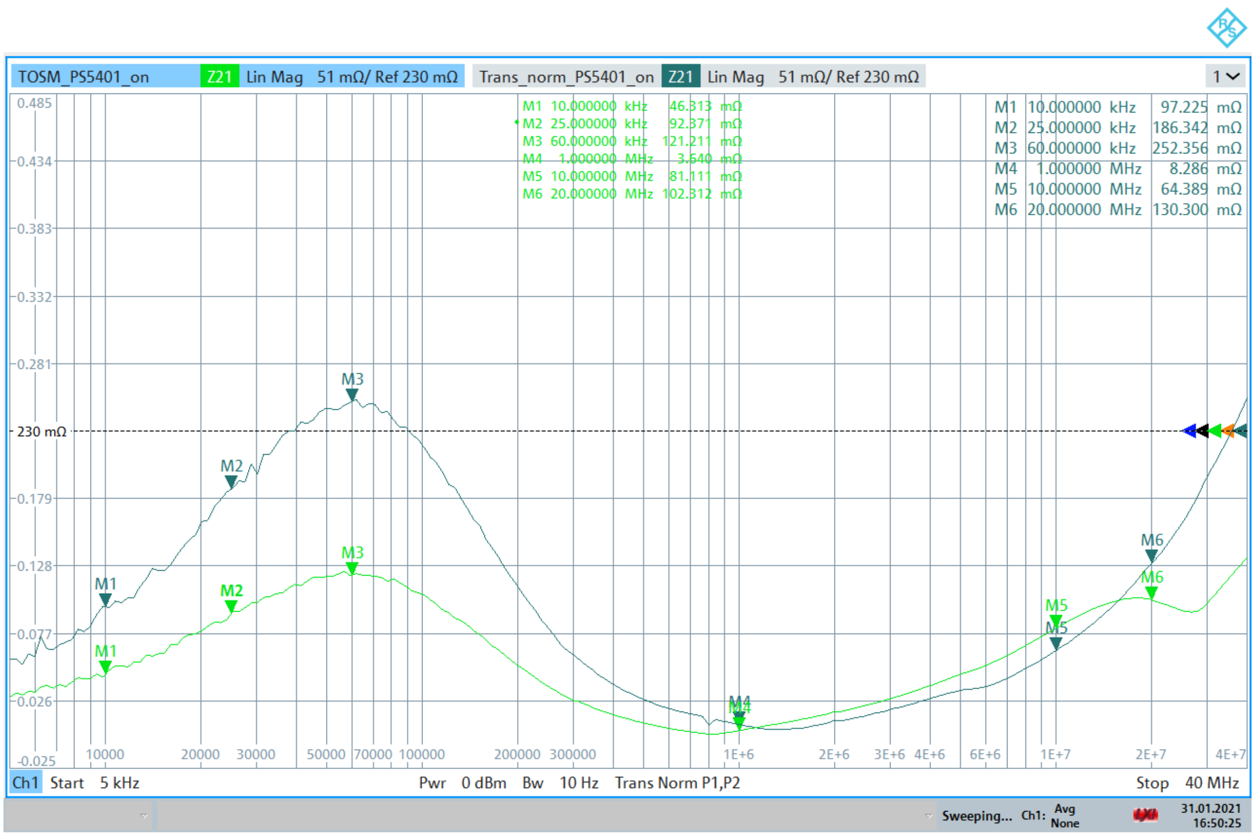

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Fig. 15 - Infineon PS5401 ON - Measurement Results using TOSM-cal method (green) vs. TRANS NORM method (blue) with ZNL6 and P2102A.

As shown by Figure 14, a 141 mΩ decrease is observed at 185 kHz with the TOSM calibrated measurement versus with the TRANS NORM calibrated measurement on the LM20143 Not Flat DUT. A similar result is also seen by Figure 15 where a 121 mΩ decease at 60 kHz is observed by using the TOSM calibration method in comparison to the TRANS NORM method.

5.0 Conclusion

The 2-port shunt-through impedance testing method shown here is the gold standard for measuring a VRM's output impedance and the control loop gain (phase) stability performance.

The P2102A browser probe allows you to very simply, quickly, and accurately make 2-port impedance measurements that help better design your PDN and provide quick GO/NO-GO testing. When impedances are measured, not only can we determine a VRM's stability, but we can also determine what the power supply distribution network is composed of. We can even create a highly accurate model of the VRM from the impedance measurement that includes time domain, frequency domain and even EMI related data. We can tell which parts of the impedance are based on control loop performance and which parts are based on printed circuit board and/or decoupling performance.

If you want to measure planes or high frequency impedance, the P2104A 1-port probes [14] can be an even better option.

As shown in this document, to make low impedance measurements with a ZNL6 VNA with the P2102A browser probe:

- It is essential to have the correct (low inductance) probes, high quality cables, and the common mode transformer (J2102B).
- You must properly calibrate your setup as this is essential to achieve high fidelity measurement and eliminate sources of test setup errors.
- A consistent repeatable contact resistance that applies consistent tip pressure is necessary. This can be done with a probe holder like the N2787A shown, ClampMan [15], or one of the probe holders from PacketMicro.

6.0 References

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