Keysight Technologies Alliance for Wireless Power (A4WP) Measurements Using an Oscilloscope (Part 3) Power and Efficiency Measurements Application Note MSO-X 4154A InfiniiVision 1.5 GHz MEGA Stop 100.0r 0.0s Auto Save Recall Print Utility Quick Help 1 00



Introduction

One of the primary instruments used when designing and testing A4WP compliant wireless charging products is an oscilloscope. Although many of the required conformance test measurements may be relatively easy to perform, some are not-to-easy. There are many advanced oscilloscope settings and measurements that you may not be aware of that can enhance the accuracy and repeatability of A4WP oscilloscope measurements.

This application note is Part 3 of a 3-part series on A4WP wireless charging measurements. This part focuses on performing power and efficiency measurements. Part 1 focuses on I_{TX_COIL} measurements during the power transfer state (non-beacon), and Part 2 focuses on I_{TX_COIL} measurements during the power save state, including beacon timing. Refer to Part 1 and Part 2 for additional A4WP testing information.

This application note provides step-by-step instructions based on using a Keysight InfiniiVision X-Series oscilloscope. Note that each individual measurement builds upon the previously documented measurement.

The following topics and measurements are covered in this document:

- De-skewing Voltage and Current Probes
- Measuring PTU and/or PRU Resonator Power
- Resonator Coupling Efficiency (RCE)
- PTU Efficiency (P_{IN DC} to PTU Coil) and PRU Efficiency (PRU Coil to P_{OUT DC})
- Selecting the Right Current Probe
- Selecting the Right Differential Active Voltage Probe

Power and efficiency measurements are not called out as required oscilloscope measurements in the A4WP Conformance Test Specification document. Transferred power and efficiency are determined theoretically based on internally reported parameters and other measurements, including measured S-parameters on PTU and PRU coils using a network analyzer. But during the design phase of PTUs and/or PRUs, engineers often need to measure these characteristics of their wireless charging system while operating under various load conditions using an oscilloscope. Using a scope you can measure the power and efficiency of various stages of power transfer of the PTU and PRU in order to optimize designs.

Power can be measured using an oscilloscope by capturing both the voltage and current waveforms, and then multiplying the two together using one of the scope's waveform math functions to create an instantaneous power waveform. Power is then measured by taking the average (mean) of the power waveform over an integer number of cycles. All of this can be achieved automatically if your scope is licensed with the Power Measurements option (DSOX3PWR, DSOX4PWR, or DSOX6PWR). However, one of the most important steps before performing power and/or efficiency measurements (manually or automatically) based on PTU and/or PRU resonators that run at 6.78 MHz, is de-skewing your voltage and current probes. A few nanoseconds difference in delay between a voltage probe and current probe can make a huge difference in the accuracy of your power and efficiency measurements at this frequency.

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De-skewing Voltage and Current Probes

Although voltage and current probes (required for power measurements) can be de-skewed manually by capturing two in-phase voltage and current signals, and then manually adjusting the skew (delay correction) of one probe relative to the other, Keysight's InfiniiVision X-Series oscilloscopes can de-skew probes automatically if licensed with the Power Measurements option. Also required is a fixture that will provide a time-aligned voltage and current signal, such as Keysight's U1880A de-skew fixture. However, you can easily create your own de-skew fixture with a few simple parts that will actually provide better de-skew accuracy. Note that you will also need the WaveGen option licensed on your InfiniiVision X-Series oscilloscope, or you can simply use an external function generator as an input signal source for your custom-made de-skew fixture.

Figure 1 shows a simple custom-made de-skew fixture that consists of just one $10-\Omega$ resistor and a BNC-to-grabber adapter. Connect the de-skew fixture to the WaveGen output of the scope, or connect it to the output of an external function generator. Set up the WaveGen (or function generator) for the following conditions:

- 1. Frequency = 6.78 MHz
- 2. Wave Shape = Sine
- 3. Output Impedance = High Z
- 4. Amplitude = 10 Vpp (5 Vpp if using a 3000X scope)
- 5. Output = Enabled (on)



Figure 1. Custom-made de-skew fixture consisting of a 10- Ω resistor.

Next, connect your differential voltage probe across the $10-\Omega$ resistor and clamp your current probe around the $10-\Omega$ resistor. Make sure that the polarity of both probes are the same. You are now ready to de-skew your probes so that you can make accurate power and efficiency measurements. Using an InfiniiVision X-Series oscilloscope with the Power Measurements option, do the following.

- 1. Default Setup (Note that this does not default WaveGen settings).
- 2. Select the Power Measurements application (Analyze menu).
- 3. Under the Analysis softkey, select the Power Quality measurement.
- 4. Under the *Signals* softkey, define which input is voltage (typically channel-1) and which input is current (typically channel-2).
- 5. Select Deskew.
- 6. If using the U1880A de-skew fixture, follow the on-screen instructions.
- 7. If using a custom-made de-skew fixture (10-Ω resistor and generator), ignore the on-screen instructions and simply press *Auto Deskew*.

Figure 2 shows that the voltage waveform (yellow trace, channel-1) and the current waveform (green trace, channel-2) after the completion of the automatic probe deskew. Prior to running the automatic de-skew, signals capture by the channel-2 current probe were delayed from signals captured by the channel-1 voltage probe by 8.44 ns, but now waveforms from both channels of the scope are almost perfectly time-aligned. Without this 8.44 de-skew correction factor, you could easily observe a delay between both traces, and any power measurements performed without the de-skew correction factor would include significant error.



Figure 2. Aligned voltage and current waveforms after running automatic probe de-skew.

The scope is now ready to use this pair of scope channels (channel-1 and channel-2) to perform a power measurement on either the PTU resonator or a PRU resonator. But if you plan to perform an efficiency measurement from PTU resonator to PRU resonator, this requires using four channels of the scope; one pair of channels for input power (typically channel-1 and channel-2) and one pair of channels for output power (typically channel-3 and channel-4). If this is the case, then you will need to perform another de-skew calibration for your second set of voltage and current probes. After running a second automatic de-skew on channel-3 and channel-4, channel-2 will be de-skewed relative to channel-1 (the reference for this pair), and channel-4 will be de-skewed relative to channel-3 (the reference for this pair). You don't need to worry about de-skewing one pair relative to the other pair.

Note that if you plan to perform efficiency measurements using one pair of probes to measure DC power, such as the PRU V_{RECT} output, then deskewing probes on the DC channel pairs is not required and will be irrelevant if performed.

Measuring PTU and/or PRU Resonator Power

Measuring various power quality parameters, including real power, apparent power, and reactive power, is very easy if your Keysight InfiniiVision oscilloscope is licensed with the Power Measurements option (DSOX3PWR, DSOX4PWR, or DSOX6PWR). After de-skewing your differential voltage and current probe, connect the probes to the resonator under test (either PTU or PRU), and insure that you observe polarity of your connections. Next, do the following:

- 1. Default Setup.
- 2. Select the Power Application (Analyze menu).
- 3. Under the Analysis softkey, select the *Power Quality* measurement.
- 4. Under the *Signals* softkey, define which channel is voltage (typically channel-1) and which input channel is current (typically channel-2).
- 5. Set Cycles = 6.
- 6. Press Auto Setup.
- 7. Press *Apply* to begin the power quality measurements.
- 8. Select AC coupling for channel-1.
- 9. Select AC coupling for channel-2.

Figure 3 shows the results of an AC Power Quality measurement on a PTU coil. The yellow trace (channel-1) is the differential voltage waveform (V_{TX_COIL}) at the resonator. The green trace (channel-2) is the current waveform (I_{TX_COIL}) at the resonator. And the purple trace is the instantaneous power waveform (V x I).



Figure 3. Measuring PTU resonator power quality, including real power.

The parameter that you are probably most interested in the "Real" power shown circled, which was 4.35 watts for this measurement example. If your measurement results for real power are negative, then you probably connected one of your probes backwards. Switch the connection polarity of one of your probes. It doesn't matter which one you switch, so long as you can get them both in-phase.

Figure 4 shows the results of an AC Power Quality measurement on a PRU coil. For this measurement the channel-3 differential voltage probe captured the PRU voltage signal (V_{RX}) and the channel-4 current probe captured the PRU current signal (I_{RX}).

Since these measurements are performed in a power transfer state (non-beacons), to improve measurement resolution on both of the above power quality measurements you can turn on waveform averaging (Acquire menu).



Figure 4. Measuring PRU resonator power quality.

Measuring Resonator Coupling Efficiency (RCE)

Resonator Coupling Efficiency (RCE) measures coil-to-coil efficiency (PTU to PRU). As mentioned earlier, measuring RCE with an oscilloscope is a non-conformance test. RCE is normally measured and theoretically determined using a network analyzer S-parameter set of measurements on PTU and PRU coils (out-of-circuit). But you can measure RCE using an InfiniiVision scope for qualitative analysis in a fully operational A4WP wireless charging system in order to optimize your wireless charging design. To perform PTU to PRU efficiency (RCE) measurement using an InfiniiVision oscilloscope, do the following:

- 1. Default Setup.
- 2. Select the Power Application (Analyze menu).
- 3. Under the Analysis softkey, select the Efficiency measurement.
- 4. Select Type = AC to AC.
- 5. Under the *Signals* softkey, define which channels are the input voltage and current channels, as well as the output voltage and current channels.
- 6. Set Duration = $2 \mu s$.
- 7. Press Auto Setup.

Since the scope's efficiency measurement was optimized for AC-to-DC switch mode power supplies that operate at lower frequencies than A4WP wireless charging systems, before performing the efficiency measurement we need to change a few setup conditions of the scope.

- 8. In each of the scope's input channel menus, (channel-1, channel-2, channel-3, and channel-4), turn OFF BW limit.
- Re-scale vertical settings (V/div and A/div) to insure that all waveforms are fully onscreen (no clipping).
- 10. Select the Power Application in Analyze menu, then select Apply.

Figure 5 shows the RCE measurement using an InfiniiVision scope. In this measurement example, the scope measured an efficiency of approximately 82%. If you observe "<" or ">" on any of the displayed measurements, this means that one or more of the waveforms is probably clipped (a portion of the waveform is off-screen). Note that only Pin (P_{TX}) power waveform will be displayed. To view and re-scale the Pout (P_{RX}) power waveform, select the Math menu to turn on the Pout waveform so that you visually re-scale it.



Figure 5. Measuring Resonator Coupling Efficiency (RCE).

Measuring PTU Efficiency (P $_{\rm IN-DC}$ to PTU Coil) and PRU Efficiency (PRU Coil to $\rm P_{OUT-DC})$

To measure PTU Efficiency, do the following:

- 1. Default Setup.
- 2. Select the Power Application (Analyze menu).
- 3. Under the Analysis softkey, select the Efficiency measurement.
- 4. Select Type = DC to AC.
- 5. Under the *Signals* softkey, define which channels are the input voltage and current channels, as well as the output voltage and current channels.
- 6. Set Duration = $2 \mu s$.
- 7. Press Auto Setup.
- 8. Turn off BW Limit on the output voltage and current channels (PTU coil).
- 9. Re-scale output channel waveforms to insure that clipping does not occur.
- 10. Select the Power Application, then select Apply.

Figure 6 shows an example of the PTU Efficiency measurement.



Figure 6. Measuring PTU efficiency (P_{IN-DC} to PTU coil).

To measure PRU Efficiency (PRU coil to P_{OUT-DC}), repeat the above procedure, except select Type = AC to DC (step #4), and turn off BW limit on the input voltage and current channels (PRU coil). Figure 7 shows an example of a PRU efficiency measurement with a measured efficiency of approximately 75%.



Figure 7. Measuring PRU efficiency (PRU to P_{OUT-DC}).

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Appendix A: Selecting the Right Current Probe

Measuring the various current and timing parameters of PTU or PRU resonator current (I_{TX_COIL} and I_{RX_COIL}) requires a clamp-on Hall-effect AC/DC current probe. This type of current probe can also be used to measure DC I_{RECT} and I_{OUT} charging currents as well. If you are using a Keysight oscilloscope, then the 50-MHz 1147B or the 100-MHz N2893A current probe are recommended. Selecting the right current probe for your A4WP measurements requires careful evaluation of the probe's specifications. The table below summarizes some of the key specifications of these two probes.



Model	Bandwidth	Max peak current (AC + DC)	Conversion factor	Insertion impedance @ 6.78 MHz	Max current @ 6.78 MHz
1147B	50 MHz	30 A 1	0.1 V/A	600-mΩ	~3.5 A-RMS
N2893A	100 MHz	30 A 1	0.1 V/A	40-mΩ	~5 A-RMS

1. Maximum 15 A peak (AC + DC) continuous if using two current probes connected to the InfiniiVision X-Series oscilloscope.

The "banner" specifications (bandwidth and maximum current) of these two probes clearly meet A4WP requirements of measuring a 6.78 MHz sine wave at up to 5 A-RMS. But these two specifications (bandwidth and maximum current) are mutually exclusive. This is true for other vendor's current probes in this class as well. Current probes have de-rated specifications as a function of input frequency. The two de-rated specifications that you need to closely evaluate are insertion impedance and maximum current at the intended measurement frequency. These specifications are only found in the user's guide and shown as charts. Figure 8 shows that the maximum de-rated current probe, which is a lower-cost current probe, is de-rated to approximately 3.5 A-RMS at 6.78 MHz. So this probe does not meet the A4WP 5 A-RMS requirement. But if your wireless charging system always runs at current levels below 3.5 A-RMS, then this may be a good choice for you. In addition, if you need to measure output DC currents, then the performance of the 1147B should be more than adequate.



Figure 8. N2893A current probe maximum de-rated current as a function of frequency.

The other important specification to consider is insertion impedance. Figure 9 shows the insertion impedance of the 100-MHz bandwidth N2893A current probe. At ~6.78 MHz, this current probe has a specified insertion impedance of ~40-m Ω , which is the best in the industry. The 50-MHz 1147B has a specified insertion impedance of ~600-m Ω at this same frequency.

Insertion impedance is the effective series loading of the current probe. All oscilloscope probes – current probes and voltage probes – will load the device under test to some degree. Another way to think of it is, they are thieves. They will steal a little bit of what is there. Voltage probes, which typically have very high impedance in parallel with the DUT, steal a little bit of current. Hall-effect current probes steal a little bit of the magnetic field, which it converts into voltage. You need to evaluate how much the added effective series impedance of the current probe will affect the operation and performance of your designs to determine which one will do the job for you. The N2893A is clearly the best probe to use to measure I_{TX_COIL} and I_{RX_COIL} in terms of maximum current and minimum insertion impedance at 6.78 MHz. But as mentioned early, the 1147B might be a good choice for lower category/class DUTs, as well as for measuring output DC currents where loading and bandwidth is not an issue.

The 1147B and N2893A both have the Keysight AutoProbe interface where it plugs into the scope's input BNC. The AutoProbe interface automatically detects that the probe is a current probe (not a voltage probe), and applies the appropriate conversion factors so that all settings (such as vertical scaling) and measurements (such as RMS) are in terms of Amperes, not Volts. A current probe is basically a transducer that actually delivers voltage to the scope that is representative of the measured current. The conversion factor for the 1147B and N2893A is 0.1 V/A. So if the probe detects a magnetic field produced by a 1 Amp current, it converts this level of current to 0.1 Volts. The scope then mathematically converts this voltage back into Amps using the conversion factor of the probe for quantitative measurement purposes.

The AutoProbe interface of the 1147B and N2893A also supplies power to the current probe. AC/DC current probes are "active" probes. This means that they have active electronic circuitry, such as amplifiers, that require power. Some AC/DC current probes require an external power supply or battery to operate.



Figure 9. N2893A current probe insertion impedance versus frequency.

Calibrating your Current Probe

Current probes require DC offset calibration and must occasionally be degaussed (demagnetized). Although Hall-effect current probes detect magnetic fields to convert into voltage, they can also build up a magnetic charge. This magnetic charge (core saturation) will induce a DC offset error.

If using the 100-MHz N2893A current probe, you can automatically calibrate DC offset along with demagnetization in the input channel's probe menu. You must disconnect the probe from any DUT, clamp the probe shut as shown in Figure 10 (push the spring lever fully forward to lock), and then just press the **OK** softkey in the probe calibration menu. The probe will first degauss itself, and then perform the offset calibration. This calibration takes about 30 seconds to complete. Note that there is also a **DEMAG** button on the probe that you should use occasionally. When you press this button, the probe demagnetizes itself (if disconnected from the DUT), but it doesn't perform an offset calibration.

If using the 50-MHz bandwidth 1147B, you can manually demagnetize the probe by first disconnecting the probe from the DUT, locked the clamp shut, and then press the **DEMAG** button on the probe. You can then manually calibrate the DC offset error contributed by the probe by rotating a thumbwheel on the probe until the waveform trace for that channel aligns with the ground indicator on the scope's display.

When making measurements on AC signals that are centered on ground, such as I_{TX_COIL} and I_{RX_COIL} , you should use AC coupling in the scope's channel menu. This will further eliminate any DC offset error contributed by the probe. So if the probe begins to build up a magnetic field that induces DC offset error in the probe, which means that it should be degaussed, AC coupling will strip out that DC error component.

Note that the scope itself can also have a DC offset/balance error. A scope's offset/balance error is typically specified around ±0.1 divisions, which can result in less-than-accurate measurements. So when performing RMS measurement on I_{TX_COIL} or I_{RX_COIL} , select the *AC RMS* – *N Cycles* measurement. This measurement will remove any DC error component contributed by the scope. If the scope that you are using only has the "RMS – Cycle" measurement, then use it. But remember that the measurement will include possible DC offset/balance errors contributed by the scope.



Figure 10. Calibrating (offset correction and degauss) the current probe.

Appendix B: Selecting the Right Differential Active Voltage Probe

Measuring power dissipation at resonators (PTU and/or PRU) requires a current probe and a differential voltage probe. Measuring resonator coupling efficiency (RCE) requires two current probes and two differential voltage probes. Keysight offers a broad range of differential voltage probes including the ones shown in Table 2.



Model	Max Input Vp-p	Bandwidth	Attenuation	Input Z
N2818A	40 Vp-p	200-MHz	10:1	1-MΩ/ 3.5- pF
N2805A	200 Vр-р	200-MHz	50:1	4-MΩ/4-pF
N2804A	600 Vр-р	300-MHz	100:1	4-MΩ/4-pF
N2790A	280 Vp-р, 2800 Vp-р	100-MHz	50:1, 500:1	8-MΩ/3.5-pF

For lower class and lower category PRUs and PTUs when maximum peak-to-peak never exceeds 40 Vp-p, the N2818A would be a good choice because it has the lowest attenuation factor (10:1) which enables this probe to more accurately measure lower level signals with higher resolution. But the input dynamic range of this probe is limited to \pm 20V AC + DC.

For all class category PRUs and PTUs, the N2790A might be the best choice because you can use this probe to not only measure resonator differential voltages using the 50:1 attenuation setting, you can also use this same probe to measure AC line voltage (110 VAC & 240 VAC) using the 500:1 attenuation setting.

You can typically use a standard 10:1 passive voltage probe (comes standard with the scope) to measure DC voltage levels at the PRU rectifier and/or V_{out} , as well as other control signals that are referenced to ground.

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Related Literature

Publication title	Publication number
InfiniiVision Oscilloscope Probes and Accessories - Selection Guide Data Sheet	5968-8153EN
InfiniiVision 4000 X-Series Oscilloscopes - Data Sheet	5991-1103EN
InfiniiVision 6000 X-Series Oscilloscopes - Data Sheet	5991-4087EN
InfiniiVision 3000T X-Series Oscilloscopes - Data Sheet	5992-0140EN
Characterizing Passive Components in Wireless Power Transfer (WPT) Systems -	5992-0771EN
Application Note	
Alliance for Wireless Power (A4WP) Measurements Using an Oscilloscope (Part 1):	5992-1109EN
$I_{_{\sf TX\ COIL}}$ Measurements during the Power Transfer State (non-beacons) - Application	
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Alliance for Wireless Power (A4WP) Measurements Using an Oscilloscope (Part 2):	5992-1110EN
I_{TX_COIL} Measurements during the Power Save State (Beacons) - Application Note	

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