Keysight Technologies
Alliance for Wireless Power (A4WP)
Measurements Using an Oscilloscope (Part 1)

$I_{TX\_COIL}$ Measurements during the Power Transfer State
(non-beacons)

Application Note
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 1 of a 3-part series on A4WP wireless charging measurements. This part focuses on performing $I_{TX\_COIL}$ measurements during the power transfer state (non-beacons). Part 2 focuses on $I_{TX\_COIL}$ measurements during the power save state (beacons), including beacon timing, and Part 3 focuses on power and efficiency measurements. Refer to Part 2 and Part 3 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 A4WP power transfer measurements are covered in this document:

- RMS Current ($I_{TX\_COIL}$)
- Frequency of $I_{TX\_COIL}$
- Transition Response Settling Time of $I_{TX\_COIL}$
- Slew Rate of $I_{TX\_COIL}$
- Selecting the Right Current Probe

Measuring various parameters of the $I_{TX\_COIL}$ current waveform, such as RMS current, Frequency, and Slew Rate, when the charging system is in a non-power save state, in other words, when there is continuous current (non-beacon current), are relatively easy to perform. When setting up the oscilloscope to perform a new set of measurements, it is always good practice to begin with a Default Setup, just in case the scope had been previously configured in a special measurement mode. Next, de-gauss (demagnetize) your current probe after a sufficient warm-up time. Current probes can build up a magnetic field (core saturation) that can induce a DC offset error. Refer to Appendix A of this document for additional information about clamp-on Hall-effect current probes.
RMS Current ($I_{TX\_COIL}$) during Power Transfer State (non-beacons)

Begin by connecting your current probe to the $I_{TX\_COIL}$ current loop measurement test point. After a PRU connection has been established, or after powering your PTU resonator with a signal generator and external power amplifier, do the following:

1. Default Setup.
2. AutoScale.

Figure 1 shows the scope’s scaling of the $I_{TX\_COIL}$ waveform after performing the AutoScale operation. This scaling may get us close to what we need for our measurements, but it is probably not optimum. The dynamic range of a scope’s analog-to-digital converter (ADC) is typically spread between the bottom and top of the scope’s display (8 divisions). If the $I_{TX\_COIL}$ waveform is scaled for just over 4 vertical divisions peak-to-peak as shown in this screen image, then current measurements will be based on using just over half of the ADC. In other words, if the scope has an 8-bit ADC, as is the case with Keysight’s InfiniiVision X-Series, as well as other scopes in this class, you will be making ~7-bit measurements. It always best to fine-tune the scope’s vertical scaling in order to maximize vertical resolution.

Most scopes have a “course” and “fine” adjustment for both vertical and horizontal scaling. The default scaling, as well as the AutoScale scaling, is typically based on “course” settings. We can do better than that. Assuming that you are using channel-1 of the scope for your $I_{TX\_COIL}$ measurements, momentarily press the channel-1 vertical scaling knob. This will put it into the “fine” scaling mode. Now rotate the channel-1 vertical scaling knob until the waveform is scaled close to full-screen (~7 division peak-to-peak) — without clipping. If you press the vertical scaling knob again, it will toggle back to the “coarse” mode.

Note that if you are automating measurements under computer/software control, rather than fine-tuning the vertical scaling manually, you can measure the peak-to-peak current after performing the AutoScale operation in order to further optimize vertical scaling. For example, if the peak-to-peak current measures 1.8 A after performing an AutoScale, set vertical scaling to 260 mA/div to obtain approximately 7 divisions of peak-to-peak deflection ($1.8 \, A / 7\, \text{div} = 257 \, \text{mA/div}$).

Figure 1. Automatic scaling of the $I_{TX\_COIL}$ waveform using AutoScale.
Now that vertical scaling has been optimized, do the following to measure the RMS current of $I_{TX\_COIL}$:

3. Set input coupling of the $I_{TX\_COIL}$ measurement channel to AC-coupling.
4. Turn on Noise Reject (Trigger Mode/Coupling menu).
5. Set timebase to 100 ns/div.
6. Set trigger level to 0.0 A.
7. Turn on Averaging = 8 (Acquire menu)
8. Turn on the “AC RMS – N Cycles” measurement on the $I_{TX\_COIL}$ input channel (typically channel-1).

Figure 2 shows the RMS current measurement on $I_{TX\_COIL}$. Since the $I_{TX\_COIL}$ RMS current measurement is based on AC current only, AC coupling will help eliminate any possible DC offset error/drift contributed by the current probe.

Figure 2. Measuring the RMS current of $I_{TX\_COIL}$.

When measuring very low-level $I_{TX\_COIL}$ signals, random noise on the input signal can sometimes induce false triggers. The Noise Reject selection will reduce the possibility of this occurring. Averaging will further reduce the effects of noise in order to provide higher resolution and more accurate measurements.

Many scopes only have an “RMS – Cycle” measurement, which will include DC offset/balance error contributed by the scope. Although AC coupling helps to eliminate probe offset errors, it does not eliminate minor offset/balance errors that may be contributed by the scope. The “AC RMS N-Cycles” measurement, which is available on Keysight’s oscilloscope, eliminates DC offset errors contributed by any source. “N-Cycles” simply means that the measurement will be performed across an integer number of waveform cycles shown on the scopes display. At a timebase setting of 100 ns/div, the AC RMS N-Cycles measurement is performed across 6 cycles of the $I_{TX\_COIL}$ waveform. This provides an additional element of averaging the measurements. Without explicitly averaging repetitive measurements, this measurement of $I_{TX\_COIL}$ provides 10 µA of measurement resolution. But if the input signal is excessively noisy, you can also turn on measurement statistics for more stable measurements based on a “mean” value of this RMS measurement.
**Frequency of I\textsubscript{TX,COIL}**

There are two different ways of measuring frequency when using an InfiniiVision X-Series oscilloscope. A standard frequency measurement on a captured waveform is actually a delta-time measurement of a single period. But Keysight’s InfiniiVision X-Series oscilloscopes also have a real-time 5-digit frequency counter, which is much more accurate if measuring continuous wave (CW) type signals, such as the I\textsubscript{TX,COIL} AC signal when charging (non-beacons). To measure frequency of I\textsubscript{TX,COIL} using both measurement techniques (just for comparison), continue with the following steps:

9. Turn on the standard *Frequency* measurement on the I\textsubscript{TX,COIL} input channel (Measurement menu).

10. Turn on the 5-digit *Frequency Counter* (Analyze menu).

**Figure 3** shows both measurements. However, the 5-digit *Frequency Counter* measurement is probably hiding the standard *Frequency* measurement on your scope. To show both measurements on-screen, drag the *Counter* window/panel over into the waveform display area (touch and drag where you see the dots).

The real-time *Frequency Counter* (yellow digits) totalsize the number of trigger crossings over a 160 ms time-span (measurement gate time) and then computes the average frequency. For 6.78 MHz, this is basically the average of more than 1,000,000 cycles of the input to provide 100 Hz of measurement resolution. The frequency should measure 6.78 MHz ±15 kHz. In the measurement example shown in Figure 3, the real-time frequency counter measurement is locked-in at 6.7800 MHz (no flipping digits). Although the standard *Frequency* measurement (orange digits) is showing just as many digits, the lower three digits are all flipping (relatively unstable). To improve the measurement resolution of the standard *Frequency* measurement, you can turn on measurement statistics and then record the “mean” value after a certain number of measurements (counts) have been taken. Although this measurement technique may be good enough, the real-time *Frequency Counter* measurement technique is faster, more accurate, and provides a higher resolution measurement (more stable). However, note that the *Frequency Counter* measurement cannot be used to measure the frequency of short and long beacons. For those measurements, which are covered in Part 2 of this 3-part series, the standard *Frequency* measurement must be used.

**Figure 3. Measuring frequency of I\textsubscript{TX,COIL}.**
Transition Response Settling Time $I_{TX,COIL}$

When PTU power levels are increased or decreased due to a PRU load change, $I_{TX,COIL}$ should have a properly-damped transition response and settle to the newly adjusted current level within 250 ms. The most difficult part of performing this timing measurement with precision is often just defining a unique trigger condition that can detect a subtle change in the $I_{TX,COIL}$ current level.

Figure 4 shows the first step in performing a power transfer state settling time measurement on $I_{TX,COIL}$ after an approximate 10% increase in current. Pulse Width triggering (negative pulse > 300 ms using the Normal trigger mode without Noise Reject) was used in this measurement example. The trigger level was set just above the positive peaks of $I_{TX,COIL}$ prior to the transition. If there is not enough difference in levels for the scope’s trigger circuitry to detect the change, then you will have to use the Auto trigger mode, and then manually Stop acquisitions when you observe a level change. However, note that Roll mode can’t be used because the math functions that will be used to precisely measure the transition settling time are disabled in Roll mode. The scope’s timebase setting will depend upon the slew rate of change. In this example, the timebase was set at 100 ms/div. At this timebase setting, waveform averaging must be turned OFF, and the Peak Detect acquisition mode should be turned on.

Figure 4. Triggering on a current level shift of $I_{TX,COIL}$ and plotting the peak values with the Max Hold waveform math function.
The purple waveform that you can see riding on top of the $I_{TX\_COIL}$ waveform is the “Max Hold” waveform math function (Math1), which plots the absolute positive-most peaks of $I_{TX\_COIL}$ with the scope’s acquisition mode set to “Peak Detect”.

Measuring the transition settling time requires a customized rise time measurement on a higher resolution version of the Max Hold waveform. This can be accomplished by applying a Smoothing math function (Math2) on the Max Hold waveform (Math1), and then expanding the resultant waveform as shown in Figure 5. To measure the transition settling time, a rise time measurement was performed using a lower measurement threshold level set at 1% and upper threshold set at 90%. In this example, we measured a transition settling of 75 ms to 90% of the steady-state current after a step change in current, which is within the specification of 250 ms.

![Figure 5. Measuring the transition settling time of an $I_{TX\_COIL}$ current level shift.](image_url)
Slew Rate of $I_{TX\_COIL}$

The slew rate of a step change in current level should not exceed approximately 100 mArms to 160 mArms/ms, depending upon the specific resonator. Continuing from the previous transition settling time measurement (Figure 5), since the smoothed Max Hold waveform (Math2) plots peak values of current, measuring the slew rate of this step change in current relative to RMS values requires a third waveform math function ($Ax + B$) to scale the smoothed Max Hold waveform. Figure 6 shows the results. In this example, “A” was set to 0.707 to scale the waveform relative to RMS values of current. A rise time measurement using a lower threshold of 45% and an upper threshold of 55% was then performed. With the scope’s cursors tracking the custom rise time measurement, the Cursors menu was selected in order to display the slew rate of this measurement ($\Delta Y/\Delta X$). In this example we measured an RMS slew rate of this step change in current of 372 mArms/s (or 0.372 mArms/ms), which is well within the range of slew rate specifications (100 mArms/ms to 160 mArms/ms).

![Figure 6. Measuring the slew rate in a step change in current relative to RMS values using the “Ax + B” waveform math function.](image)

Also shown in this example are measurements of the initial steady-state RMS current level before the transition (Base = 295 mA), the final steady-state RMS current level after the transition (Top = 323 mA), the maximum RMS current level during the transition (Max = 326 mA), and the percentage overshoot that occurred during the transition (Over = 9.6%). But note that 9.6% overshoot relative to the transition was just 3 mA, or 0.9% above the final steady-state current level. The overshoot measurement can help determine if the response is over-damped.
Appendix A: Selecting the Right Current Probe

Measuring the various current and timing parameters of PTU or PRU resonator current (\(I_{\text{TX_COIL}}\) and \(I_{\text{RX_COIL}}\)) requires a clamp-on Hall-effect AC/DC current probe. This type of current probe can also be used to measure DC \(I_{\text{RECT}}\) and \(I_{\text{OUT}}\) 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.

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

\(^1\) 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 7 shows that the maximum de-rated current of the N2893A is approximately 5 A-RMS at 6.78 MHz. The 50-MHz bandwidth 1147B 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 7: N2893A current probe maximum de-rated current as a function of frequency.
The other important specification to consider is insertion impedance. Figure 8 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-mΩ, which is the best in the industry. The 50-MHz 1147B has a specified insertion impedance of ~600-mΩ at this same frequency.

![Figure 8. N2893A current probe insertion impedance versus frequency.](image)

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.
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 9 (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 9. Calibrating (offset correction and degauss) the current probe.](image)
Related Literature

<table>
<thead>
<tr>
<th>Publication title</th>
<th>Publication number</th>
</tr>
</thead>
<tbody>
<tr>
<td>InfiniiVision Oscilloscope Probes and Accessories - Selection Guide Data Sheet</td>
<td>5968-8153EN</td>
</tr>
<tr>
<td>InfiniiVision 4000 X-Series Oscilloscopes - Data Sheet</td>
<td>5991-1103EN</td>
</tr>
<tr>
<td>InfiniiVision 6000 X-Series Oscilloscopes - Data Sheet</td>
<td>5991-4087EN</td>
</tr>
<tr>
<td>InfiniiVision 3000T X-Series Oscilloscopes - Data Sheet</td>
<td>5992-0140EN</td>
</tr>
<tr>
<td>Characterizing Passive Components in Wireless Power Transfer (WPT) Systems -</td>
<td>5992-0771EN</td>
</tr>
<tr>
<td>Application Note</td>
<td></td>
</tr>
<tr>
<td>Alliance for Wireless Power (A4WP) Measurements Using an Oscilloscope (Part 2):</td>
<td>5992-1110EN</td>
</tr>
<tr>
<td>$I_{\text{TX,COL}}$ Measurements during the Power Save State (Beacons) -</td>
<td></td>
</tr>
<tr>
<td>Application Note</td>
<td></td>
</tr>
<tr>
<td>Alliance for Wireless Power (A4WP) Measurements Using an Oscilloscope (Part 3):</td>
<td>5992-1111EN</td>
</tr>
<tr>
<td>Power and Efficiency Measurements - Application Note</td>
<td></td>
</tr>
</tbody>
</table>
Evolving Since 1939

Our unique combination of hardware, software, services, and people can help you reach your next breakthrough. We are unlocking the future of technology. From Hewlett-Packard to Agilent to Keysight.

myKeysight

myKeysight
www.keysight.com/find/mykeysight
A personalized view into the information most relevant to you.

http://www.keysight.com/find/emt_product_registration
Register your products to get up-to-date product information and find warranty information.

Keysight Services

www.keysight.com/find/service
Keysight Services can help from acquisition to renewal across your instrument’s lifecycle. Our comprehensive service offerings—one-stop calibration, repair, asset management, technology refresh, consulting, training and more—helps you improve product quality and lower costs.

Keysight Assurance Plans

www.keysight.com/find/AssurancePlans
Up to ten years of protection and no budgetary surprises to ensure your instruments are operating to specification, so you can rely on accurate measurements.

Keysight Channel Partners

www.keysight.com/find/channelpartners
Get the best of both worlds: Keysight’s measurement expertise and product breadth, combined with channel partner convenience.