

How to Make Successful Harmonic Measurements

The Challenge

Affordable, clean energy is a sustainable development goal intended to drive higher efficiency in products today. Efficiency and power quality standards for appliances and equipment used in residential and commercial buildings are designed to reduce energy costs. Generating reliable power is paramount in critical generation systems such as those in aerospace, military, and standby power applications. Power standards for generation systems typically focus on ensuring robust power networks. The efficiency and reliability of power networks are maximized by increasing the power quality of the system. Harmonic content is a key contributor to low power quality, and agency standards are written to ensure manufacturers take action to measure and control harmonics.

This application note provides a guide for making harmonic measurements with a power analysis instrument.

Necessities

Acquiring accurate measurement of the harmonic content with the highest fidelity possible requires a high-precision instrument with guaranteed accuracy statements for both fundamental frequencies and harmonic content (Figures 1-2). Yokogawa Test&Measurement offers a range of power analyzers and power scopes to address these needs.

Voltage	
DC	$\pm(0.02\% \text{ of reading} + 0.05\% \text{ of range})$
$0.1 \text{ Hz} \leq f < 10 \text{ Hz}$	$\pm(0.03\% \text{ of reading} + 0.05\% \text{ of range})$
$10 \text{ Hz} \leq f < 45 \text{ Hz}$	$\pm(0.03\% \text{ of reading} + 0.05\% \text{ of range})$
$45 \text{ Hz} \leq f \leq 66 \text{ Hz}$	$\pm(0.01\% \text{ of reading} + 0.02\% \text{ of range})$
$66 \text{ Hz} < f \leq 1 \text{ kHz}$	$\pm(0.03\% \text{ of reading} + 0.04\% \text{ of range})$
$1 \text{ kHz} < f \leq 10 \text{ kHz}$	$\pm(0.1\% \text{ of reading} + 0.05\% \text{ of range})$ Add $0.015\% \times f$ of reading (lower than 10 V range)
$10 \text{ kHz} < f \leq 50 \text{ kHz}$	$\pm(0.3\% \text{ of reading} + 0.1\% \text{ of range})$
$50 \text{ kHz} < f \leq 100 \text{ kHz}$	$\pm(0.6\% \text{ of reading} + 0.2\% \text{ of range})$
$100 \text{ kHz} < f \leq 500 \text{ kHz}$	$\pm\{(0.006 \times f)\% \text{ of reading} + 0.5\% \text{ of range}\}$
$500 \text{ kHz} < f \leq 1 \text{ MHz}$	$\pm\{(0.022 \times f - 8)\% \text{ of reading} + 1\% \text{ of range}\}$
Bandwidth DC to 10 MHz (Typical, -3 dB)	

Current	
DC	$\pm(0.02\% \text{ of reading} + 0.05\% \text{ of range})$
$0.1 \text{ Hz} \leq f < 10 \text{ Hz}$	$\pm(0.03\% \text{ of reading} + 0.05\% \text{ of range})$
$10 \text{ Hz} \leq f < 45 \text{ Hz}$	$\pm(0.03\% \text{ of reading} + 0.05\% \text{ of range})$
$45 \text{ Hz} \leq f \leq 66 \text{ Hz}$	$\pm(0.01\% \text{ of reading} + 0.02\% \text{ of range}) \pm 0.5 \mu\text{A}^*$ *only direct input of 760902
$66 \text{ Hz} < f \leq 1 \text{ kHz}$	$\pm(0.03\% \text{ of reading} + 0.04\% \text{ of range})$
$1 \text{ kHz} < f \leq 10 \text{ kHz}$	$\pm(0.1\% \text{ of reading} + 0.05\% \text{ of range})$
$10 \text{ kHz} < f \leq 50 \text{ kHz}$	$\pm(0.3\% \text{ of reading} + 0.1\% \text{ of range})$
$50 \text{ kHz} < f \leq 100 \text{ kHz}$	$\pm(0.6\% \text{ of reading} + 0.2\% \text{ of range})$
$100 \text{ kHz} < f \leq 200 \text{ kHz}$	$\pm\{(0.00725 \times f - 0.125)\% \text{ of reading} + 0.5\% \text{ of range}\}$
$200 \text{ kHz} < f \leq 500 \text{ kHz}$	$\pm\{(0.00725 \times f - 0.125)\% \text{ of reading} + 0.5\% \text{ of range}\}$
$500 \text{ kHz} < f \leq 1 \text{ MHz}$	$\pm\{(0.022 \times f - 8)\% \text{ of reading} + 1\% \text{ of range}\}$
Bandwidth Direct input: DC to 5 MHz (Typical, -3 dB) External Current Sensor input: DC to 5 MHz (Typical, -3 dB)	

Power (PF=1)	
DC	$\pm(0.02\% \text{ of reading} + 0.05\% \text{ of range})$
$0.1 \text{ Hz} \leq f < 10 \text{ Hz}$	$\pm(0.08\% \text{ of reading} + 0.1\% \text{ of range})$
$10 \text{ Hz} \leq f < 30 \text{ Hz}$	$\pm(0.08\% \text{ of reading} + 0.1\% \text{ of range})$
$30 \text{ Hz} \leq f < 45 \text{ Hz}$	$\pm(0.05\% \text{ of reading} + 0.05\% \text{ of range})$
$45 \text{ Hz} \leq f \leq 66 \text{ Hz}$	$\pm(0.01\% \text{ of reading} + 0.02\% \text{ of range})$
$66 \text{ Hz} < f \leq 1 \text{ kHz}$	$\pm(0.05\% \text{ of reading} + 0.05\% \text{ of range})$
$1 \text{ kHz} < f \leq 10 \text{ kHz}$	$\pm(0.15\% \text{ of reading} + 0.1\% \text{ of range})$ Add $0.01\% \times f$ of reading (lower than 10 V range)
$10 \text{ kHz} < f \leq 50 \text{ kHz}$	$\pm(0.3\% \text{ of reading} + 0.2\% \text{ of range})$
$50 \text{ kHz} < f \leq 100 \text{ kHz}$	$\pm(0.7\% \text{ of reading} + 0.3\% \text{ of range})$
$100 \text{ kHz} < f \leq 200 \text{ kHz}$	$\pm\{(0.008 \times f)\% \text{ of reading} + 1\% \text{ of range}\}$
$200 \text{ kHz} < f \leq 500 \text{ kHz}$	$\pm\{(0.008 \times f)\% \text{ of reading} + 1\% \text{ of range}\}$
$500 \text{ kHz} < f \leq 1 \text{ MHz}$	$\pm\{(0.048 \times f - 20)\% \text{ of reading} + 1\% \text{ of range}\}$

Figure 1. Example power analyzer voltage, current, and power accuracy specifications for fundamental frequencies.

Frequency	Voltage, Current
$0.1 \text{ Hz} \leq f < 10 \text{ Hz}$	$\pm(0.01\% \text{ of reading} + 0.03\% \text{ of range})$
$10 \text{ Hz} \leq f < 45 \text{ Hz}$	$\pm(0.01\% \text{ of reading} + 0.03\% \text{ of range})$
$45 \text{ Hz} \leq f \leq 66 \text{ Hz}$	$\pm(0.01\% \text{ of reading} + 0.03\% \text{ of range})$
$66 \text{ Hz} < f \leq 440 \text{ Hz}$	$\pm(0.01\% \text{ of reading} + 0.03\% \text{ of range})$
$440 \text{ Hz} < f \leq 1 \text{ kHz}$	$\pm(0.01\% \text{ of reading} + 0.03\% \text{ of range})$
$1 \text{ kHz} < f \leq 10 \text{ kHz}$	$\pm(0.01\% \text{ of reading} + 0.03\% \text{ of range})$
$10 \text{ kHz} < f \leq 50 \text{ kHz}$	$\pm(0.05\% \text{ of reading} + 0.1\% \text{ of range})$
$50 \text{ kHz} < f \leq 100 \text{ kHz}$	$\pm(0.1\% \text{ of reading} + 0.2\% \text{ of range})$
$100 \text{ kHz} < f \leq 500 \text{ kHz}$	$\pm(0.1\% \text{ of reading} + 0.5\% \text{ of range})$
$500 \text{ kHz} < f \leq 1.5 \text{ MHz}$	$\pm(0.5\% \text{ of reading} + 2\% \text{ of range})$

Frequency	Power
$0.1 \text{ Hz} \leq f < 10 \text{ Hz}$	$\pm(0.02\% \text{ of reading} + 0.06\% \text{ of range})$
$10 \text{ Hz} \leq f < 45 \text{ Hz}$	$\pm(0.02\% \text{ of reading} + 0.06\% \text{ of range})$
$45 \text{ Hz} \leq f \leq 66 \text{ Hz}$	$\pm(0.02\% \text{ of reading} + 0.06\% \text{ of range})$
$66 \text{ Hz} < f \leq 440 \text{ Hz}$	$\pm(0.02\% \text{ of reading} + 0.06\% \text{ of range})$
$440 \text{ Hz} < f \leq 1 \text{ kHz}$	$\pm(0.02\% \text{ of reading} + 0.06\% \text{ of range})$
$1 \text{ kHz} < f \leq 10 \text{ kHz}$	$\pm(0.02\% \text{ of reading} + 0.06\% \text{ of range})$
$10 \text{ kHz} < f \leq 50 \text{ kHz}$	$\pm(0.1\% \text{ of reading} + 0.2\% \text{ of range})$
$50 \text{ kHz} < f \leq 100 \text{ kHz}$	$\pm(0.2\% \text{ of reading} + 0.4\% \text{ of range})$
$100 \text{ kHz} < f \leq 500 \text{ kHz}$	$\pm(0.2\% \text{ of reading} + 1\% \text{ of range})$
$500 \text{ kHz} < f \leq 1.5 \text{ MHz}$	$\pm(1\% \text{ of reading} + 4\% \text{ of range})$

Figure 2. Example power analyzer voltage, current, and power accuracy specifications for harmonic measurements.

Setting Up for Success

The following is a list of key instrument settings for a successful harmonic measurement:

1. Wiring

Please see the appropriate “Getting Started” guide for an instrument’s wiring instructions. For this document, we will assume that a single-phase load is used.

Once connections are made, users must configure the wiring system in the power analyzer setup menu. This is done through the Wiring menu of the instrument or configuration software.

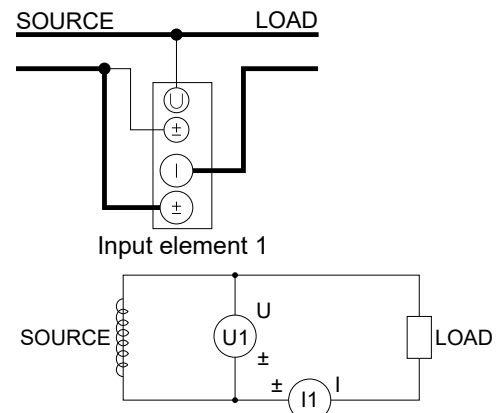


Figure 3. Wiring diagram for a single-phase load (1P2W) connected to a power analyzer.

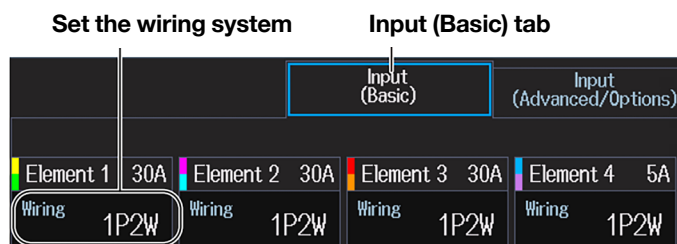


Figure 4. Wiring configuration for (1P2W).

2. Voltage and Current Range - Auto

Power analyzers typically have 10-15 range settings for voltage and current for making accurate measurements appropriate to the size of the load. Configuring the range improperly can significantly impact the accuracy of the voltage and power readings.

The Auto Range setting automatically determines the most appropriate measurement limits to ensure the entire signal is read with optimal accuracy. This includes automatically adjusting the crest factor setting to account for the shape of the input signal (PWM vs. sinusoid, noisy vs. clean, etc.). If the range is known never to change (e.g., in the case of line voltage), a fixed range instead of auto can be set.

Current range (example of element 1)



Figure 5. Users can toggle the Auto button to ON for each of the elements.

3. Scaling – Current Transformer (CT) scaling if CTs are used, Voltage Transformer (VT) scaling if VTs are used

For high currents, it is common to use a CT for safe, galvanically-isolated measurement of high currents. Although not as common, VTs or dividers are also used to step-down a higher voltage to a range that is compatible with the power analyzer. If the measurement setup uses CTs or VTs for this purpose, it is necessary to set the scaling ratio on the power analyzer accordingly. Unless the scaling is set properly in the element menu, power readings will not be accurate. Users can find scaling in the Setup menu under the field labeled Scaling, directly below the Current Range field.

VT ratio, CT ratio, and power coefficient

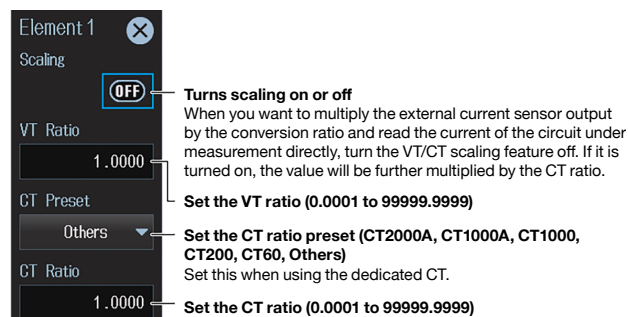


Figure 6. Setting VT and CT ratios.

4. Sync Source

For the best possible power accuracy, the power analyzer requires a precise measurement of the waveform's cycle period (fundamental frequency). The signal on which the measurement period is made is referred to as the sync source. The power analyzer uses the current and voltage measurements over this measurement period to calculate power, root mean square (rms) values, harmonic distortion, and many other values that depend on a time-integration or frequency reading. This signal is generally chosen to be the cleanest sinusoidal waveform available. In the case of devices connected to the grid or wall, the voltage waveform (e.g., U1) is typically sinusoidal and representative of the fundamental frequency. In an inverter system driving an inductive load, this would be the current waveform (e.g., I1).

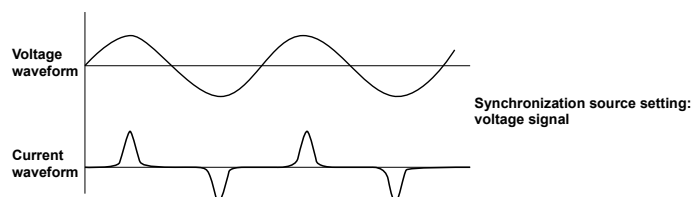


Figure 7. The frequency filter and synchronization source ensure accurate detection of the fundamental frequency. The PLL provides the proper sampling frequency.

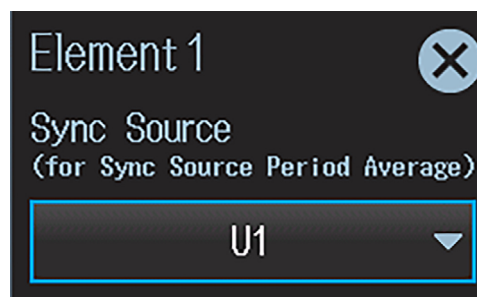


Figure 8. Sync source setting (voltage or current).

5. Frequency Filter

To accurately identify the cycle period's zero-crossing events in the sync source, the signal measurement should be clean enough to avoid crossing zero more than once per rising/falling edge. The frequency filter ensures that noise will not affect the zero-crossing detection of the fundamental frequency - this is essential for harmonic analysis.

Input Signal Frequency	Cutoff Frequency of the Frequency Filter
100 Hz or less	0.1 kHz
1 kHz or less	1 kHz
100 kHz or less	100 kHz

Figure 9. Recommended settings for frequency filter.

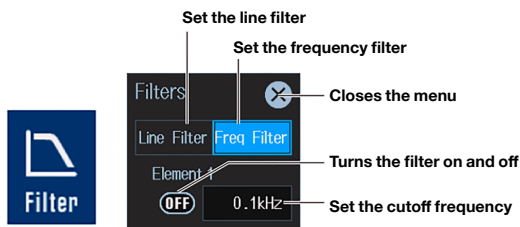


Figure 10. To enable the frequency filter, press the Filter icon from the Setup menu and toggle the ON button under the input elements.

6. Phase-Locked Loop (PLL) Source

Harmonics are defined as voltages or currents that operate at frequencies that are integral (whole number) multiples of the fundamental frequency. Power analyzers use the fast Fourier transform (FFT) to identify how much spectral content exists at each integer "bin or bucket," a.k.a. harmonic. The resolution of an FFT is defined as the sampling rate divided by the number of data points in the FFT. The power analyzer must "tune" the sample rate for harmonic measurements in real time to ensure the resolution of the FFT falls on an integer multiple of the fundamental frequency. Power analyzers use a PLL circuit to track the fundamental frequency and generate the appropriate sampling rate. The setting for the PLL circuit can be voltage or current. Typically, for grid-tied systems, this will be voltage; for inverter driven motors, it will be current.



Figure 11. PLL source setting for detecting the fundamental frequency of the voltage signal.

Harmonic Orders and Total Harmonic Distortion

Harmonic Orders

The maximum and minimum order settings determine the range of harmonic content computed. These settings will have an impact on the number of individual harmonics that are measured, the total harmonic content measurements (e.g., U(total)), and the total harmonic distortion computations.

Total Harmonic Distortion (THD)

THD is the ratio of the rms of the harmonic content, expressed as a percentage of the fundamental frequency or total current. It considers harmonic components up to the 50th order but specifically excludes interharmonics. Harmonic components of orders greater than 50 may be included when necessary. The higher the percentage, the more distorted the waveform. Two power analyzer settings for THD correspond to two equations defined by CSA and IEC, based on the denominator of the equation.

$$I_{THD}(\%) : \frac{\sqrt{\sum_{k=2}^{\max} I(k)^2}}{I(\text{total})} \times 100 \quad \text{CSA} \quad I_{THD}(\%) : \frac{\sqrt{\sum_{k=2}^{\max} I(k)^2}}{I(1)} \times 100 \quad \text{IEC}$$

Figure 12. CSA THD equation is a percentage of the total current, whereas the IEC equation is a percentage of the fundamental.

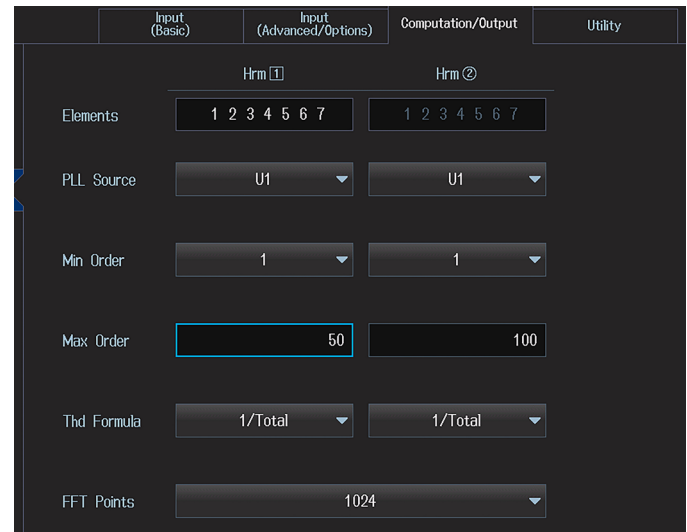


Figure 13. Setting PLL to measure 50 harmonic orders from the fundamental on U1. THD equation set for 1/total (IEC).

Line Filter and Harmonics Filter

Line Filter

Unwanted, conducted, or radiated electrical noise in signals feeding the power analyzer can be a nuisance to obtaining accurate power readings. One method for determining the presence of these signals and mitigating them is to use the internal line filter of the power analyzer. Since this filter is in series with the voltage and current measurements, experimenting with its cutoff frequency can help to identify sources of noise in the input signal and remove them. A good starting point to prevent aliasing is 1MHz. However, the ideal cutoff frequency also depends on other factors for a test's specific measurement conditions.

For example, when measuring a DC bus, it may be appropriate to set a low cutoff frequency that is close to that of an expected DC ripple (or lower if the ripple's impact is being excluded). Likewise, when using an external current measurement device, it makes sense to set a line filter close to the cutoff frequency for that device, since any power delivered above that frequency would be noise (e.g., LEM CT's have a bandwidth in the 100kHz region).

Harmonics Filter

The harmonics filter is a special feature that applies only to the harmonic measurements made by the power analyzer. This filter is in parallel with all other measurements and only impacts the measurements denoted by harmonic order or total harmonic distortion figures (e.g., Irms(10)). This filter protects against potential aliasing in harmonic measurements due to the varying sample rate applied by the PLL when performing the FFT computation. This filter should be set near or just beyond the maximum harmonic order of interest. Instruments that do not have a dedicated harmonic filter should use the line filter when aliasing is of concern.

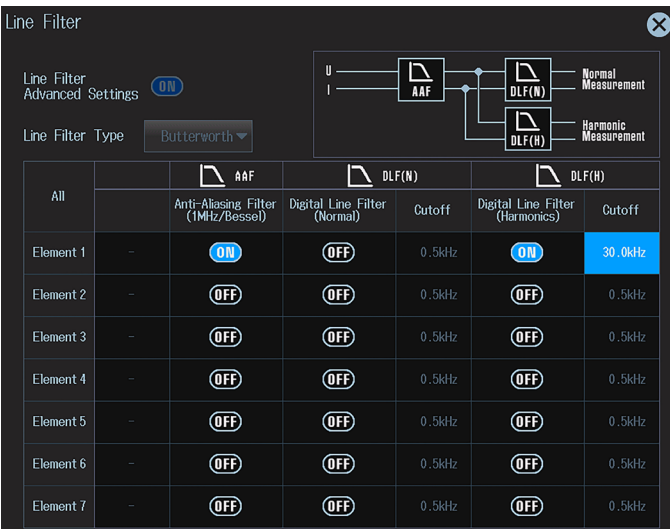


Figure 14. Line filter set for 1MHz on all measurements. Harmonic filter example setting of 30kHz for 50 orders of interest at 400Hz fundamental.

Setup Computations

User-defined computations are very powerful tools that provide efficiency gains by eliminating post-processing. Equations are entered into the power analyzer for real-time computation versus the "collect and compute later" methods using spreadsheets or computational packages after collecting data. Figures 15 and 16 show the IEEE-519 definition for total demand distortion (TDD) and an example implementation in real-time math. TDD is the ratio of the rms of the harmonic content, expressed as a percentage of the maximum demand current. The difference between the TDD equation and the THD equation is the denominator, IL. IL equals the sum of all currents corresponding to maximum demand during each of the 12 previous months, divided by 12.

$$I_{TDD} : \frac{\sqrt{\sum_{k=2}^{max} I(k)^2}}{I_L}$$

Figure 15. The equation for TDD is similar to THD, but with a different denominator.

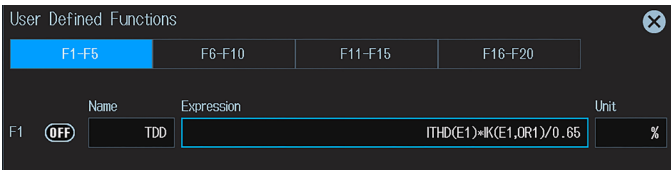


Figure 16. Example user-defined conversion of THD(%fund) to TDD, where IL is a constant.

Displaying Measurements

Harmonic measurements can be displayed by a variety of methods on the power analyzer: as a single numeric component for that order (Figure 17), in a list display of even and odd orders with percentage contributions (Figure 18), in a bar display showing the magnitude of each harmonic order bin with cursors (Figure 19), or as a percentage of the total.

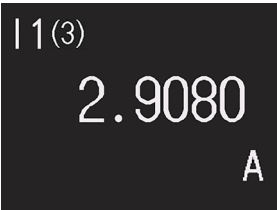


Figure 17. Numeric display of third harmonic of I1.



Figure 18. List display of harmonic components with percentage contribution.

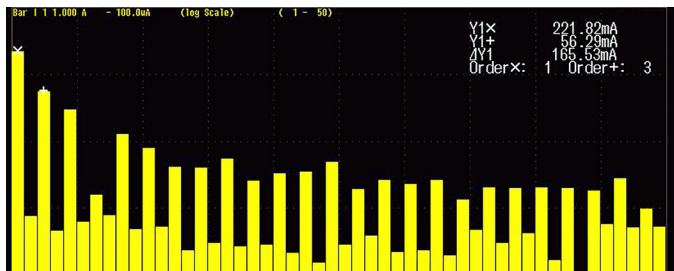


Figure 19. Bar display of harmonic components by each harmonic bin and magnitude.

Summary

Energy efficiency and reliability are driving factors behind agency standards for electrical and electronic products. Ensuring high power quality is essential for reliability and efficiency, where harmonic content is a significant contributor. High-precision instruments are required to meet the accuracy demands of agency standards, but neglecting settings such as PLL, sync source, and filtering can result in a compromised measurement. Proper attention to accuracy and instrument settings will ensure successful measurements.

Learn more about [Yokogawa Test&Measurement power analyzer solutions](#).

For more troubleshooting, please visit the [Yokogawa Test&Measurement FAQ](#) page or [contact a member of the Yokogawa support team](#).

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Yokogawa has been developing measurement solutions for 100 years, consistently finding new ways to give R&D teams the tools they need to gain the best insights from their measurement strategies. The company has pioneered accurate power measurement throughout its history and is the market leader in digital power analyzers.

Yokogawa instruments are renowned for maintaining high levels of precision and for continuing to deliver

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Yokogawa takes pride in its reputation for quality, both in the products it delivers - often adding new features in response to specific client requests - and the level of service and advice provided to clients, helping to devise measurement strategies for even the most challenging environments.

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