

Keysight Technologies

Power Conversion Efficiency Measurement Methods

Application Note

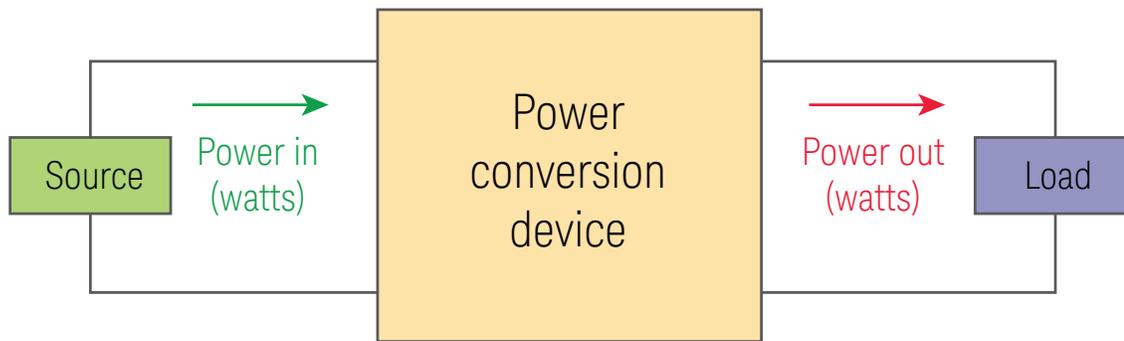
What is power conversion efficiency?

Efficiency is an assessment of how well time and effort are used to accomplish a specific task. If that task is the conversion of one form of power to another, the efficiency of the conversion indicates how well the power conversion is implemented. For an electrical power conversion process, efficiency is measured simply by dividing the output power in watts by the input power in watts and is expressed as a percentage. In power electronics, the Greek letter eta (η) is used to represent efficiency. See Figure 1.

A perfect electrical power conversion process would have an efficiency of 100 percent. However, achieving 100 percent efficiency is not possible, because all real-life electronics lose some energy as heat. Some of the input power is used for the power conversion process itself, so that input power does not make it to the output. As a result, the efficiency must be less than 100 percent.

Why is power conversion efficiency important?

Clearly, the higher the efficiency of a power conversion process, the less power is wasted. Wasted power has many costs: money, as we pay for consumed energy; time, as we have to recharge our battery-operated devices more frequently; product size, as the heat generated by wasted power must be properly dissipated; and environmental pollution, as more energy has to be generated to support the wasted power. To lower the costs associated with power conversion processes, engineers put great effort into maximizing the efficiencies of those processes. International standards limit AC-mains-powered household-electrical appliance power consumption. For example, in the United States, the U.S. Department of Energy (DOE) established energy efficiency standards that products must meet. Additionally, the ENERGY STAR program promotes voluntary compliance to standards that are even more stringent than the DOE standards. These programs highlight the importance of properly designing your power conversion processes to consume less energy and maximize efficiency. Furthermore, rapid advances in the HEV/EV (hybrid electric vehicle/electric vehicle) markets are driving the need for higher efficiency power conversion techniques as vehicle electrification proliferates. All of these developments contribute to your need to properly measure and manage your design's power consumption.



$$\text{Efficiency}(\%) = \eta = \frac{\text{Power out (W)}}{\text{Power in (W)}} \times 100$$

Figure 1. Efficiency (η) is output power in watts divided by input power in watts.

How is power conversion efficiency measured?

Because power conversion efficiency is really just the ratio of two power measurements, how efficiency is measured is really a question about how power is measured. Real power, measured in watts, is the power that does work or generates heat. It is the rate at which energy is consumed. The method used to measure electrical power depends on the form taken by the power signals. For simple DC signals where the voltage and current are constant over time, real power in watts is simply the product of the measured DC voltage and DC current. You could use a standard multimeter for these measurements. However, for AC signals where the voltage and/or current change over time, real power is more difficult to measure and dictates the use of more specialized equipment.

To get real power in watts, the instantaneous voltage with time, $v(t)$, must be multiplied by the instantaneous current with time, $i(t)$, to get the instantaneous power with time, $p(t)$. Because this instantaneous power is changing over time, you must calculate an average value by integrating the power over an integer number of cycles and dividing by the total integration time to get the average. This calculation yields the watts dissipated by the device in a circuit with voltage $v(t)$ across it and current $i(t)$ through it. Assuming that the voltage and current are both periodic waveforms of period T , the strict mathematical way to express the power calculation for a periodic waveform of period T is this:

$$\text{Average power in watts} = \frac{1}{T} \int_0^T v(t) * i(t) dt = \frac{1}{T} \int_0^T p(t) dt$$

Below are more details about these measurements and the equipment used to make them.

Multimeters for power and efficiency measurements

A special case of the above average-power-in-watts equation is when the voltage and current are DC, which means they are constant over time. This is the only situation where a multimeter can be used to provide measurements to calculate real power in watts. Multimeters are good for making simple, single measurements such as AC or DC voltage, AC or DC current, or resistance, among other things, but there is no direct power measurement function. Measuring power requires measuring both voltage and current simultaneously and a typical multimeter can measure only one parameter at a time. So to measure power with a multimeter, either you must use two separate multimeters (one for voltage; one for current) or you can use the same meter to measure two parameters, but at different times. If the voltage

and current are both purely DC (constant with time), then it does not matter if the voltage and current are measured at different times; by definition, they did not change. While this is rare, it is possible, and again, it is the only time when a multimeter can provide measurements to calculate watts.

If either the voltage or current signal is AC (changes with time), you cannot use a multimeter to provide measurements to calculate power in watts. The multimeter's AC voltage and AC current functions measure RMS (root-mean-square) values, and when these are multiplied together, you get apparent power in VA (volt-amperes), not real power in watts. Real power in watts is the important power measurement to use in efficiency calculations.

Oscilloscopes for power and efficiency measurements

Because the average-power-in-watts measurement involves capturing both voltage and current simultaneously over time, an oscilloscope is a good instrument for this task. With the right voltage and current probes, scopes can easily capture voltage and current waveforms versus time. However, obtaining a power measurement in watts as a result of these waveforms is more challenging. Basic scopes with limited capability will not enable you to do this. But many scopes have math functions that allow you to multiply waveforms together. If you use this capability and multiply the voltage waveform times the current waveform, you will get an instantaneous power waveform. This waveform is instantaneous volt-amperes rather than the desired watts, so you will need to use additional scope measurement functionality to get watts. For example, if your scope has a built-in measurement that calculates the average value of a waveform, you can apply that measurement function to the instantaneous power waveform to get watts. Be sure to do so over an exact integer number of cycles to get an accurate result. To get efficiency of a power conversion device, you will have to do this using four channels: two for the voltage and current for the input power, and two for the voltage and current for the output power. You can then calculate efficiency by dividing the output power in watts by the input power in watts. Figures 2 and 3 show a scope power measurement example testing a microinverter connected to a solar array simulator on its input (~31 V mostly DC) and the AC power grid on its output (~240 Vac). The input power measures 238.245 W and the output power measures 230.814 W, which yields a calculated efficiency of 96.88 percent.

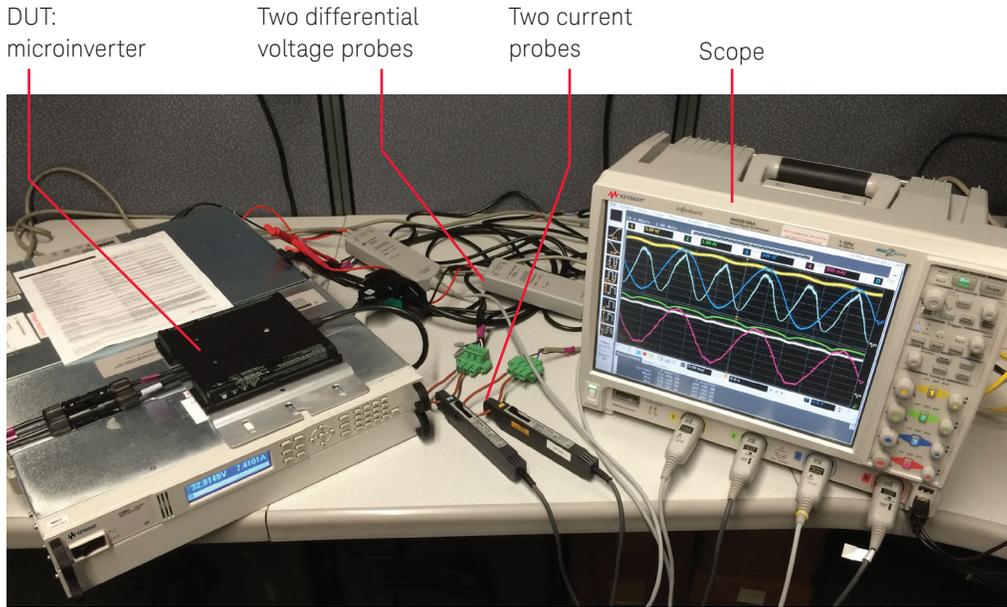


Figure 2. Four-channel Keysight scope uses math to produce microinverter input and output power waveforms from voltage and current waveforms. Then, power waveform average measurements yield watts, from which efficiency can be calculated.

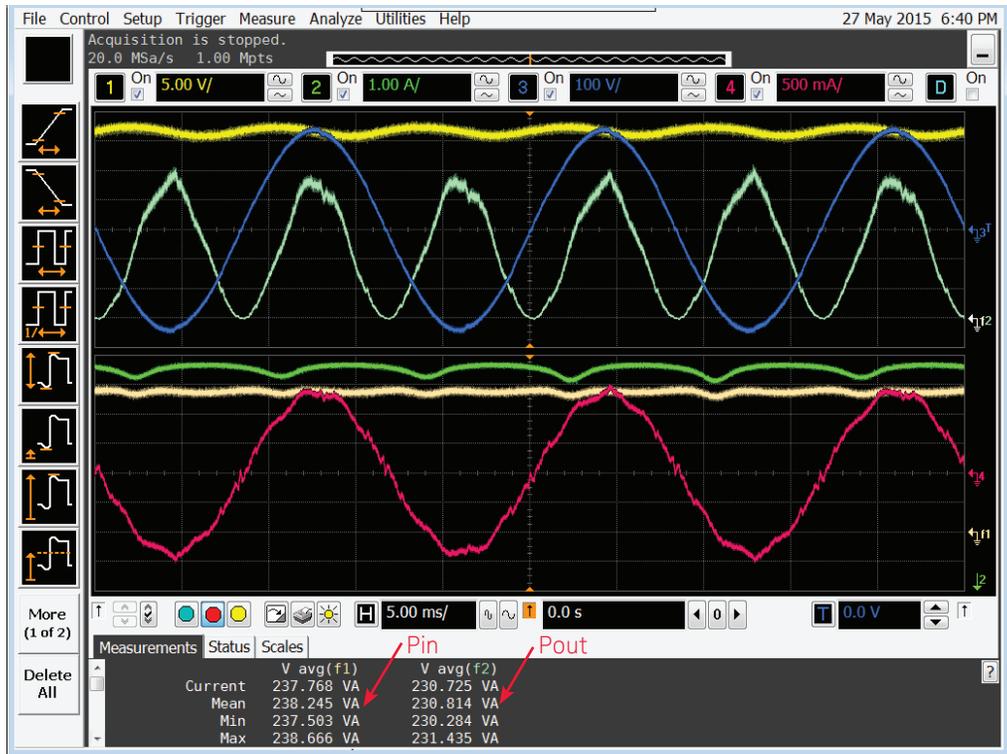


Figure 3. Close-up of scope screenshot shows math power result. Mean input power is 238.245 W and mean output power is 230.814 W, yielding a calculated efficiency of 96.88% for this microinverter under specific operating conditions.

Some oscilloscopes have very specific power measurement options that greatly simplify the acquisition of these measurements. For example, Keysight InfiniiVision 4000 and 6000 X-Series oscilloscopes have power measurement applications (DSOX4PWR and DSOX6PWR) that can measure efficiency directly by using all four channels on the scope and doing the power and efficiency calculations within the option. Scopes can provide acceptable power and efficiency type measurements on power conversion devices, however, their true power measurement benefits are revealed when they are used to look at power waveforms inside the power conversion device rather than from end to end outside the device. Keysight oscilloscope power applications are helpful when you need to analyze the reliability, efficiency, and performance of your switching and linear power supplies, especially when looking at high-frequency switching losses on power conversion circuits and components.

While oscilloscopes provide you with excellent bandwidth functionality, their voltage measurement accuracy is mediocre, mainly due to a typical design that offers 8-bit vertical resolution. Additionally, most scopes have earth-ground-referenced inputs, requiring you to use differential probes, which adds complexity to the setup and increases measurement error. Current probes are accurate to only a few percent and are notorious for drifting, so you must be sure to degauss and zero them often. To get accurate power measurements, the voltage and current waveforms must be acquired simultaneously. If high-frequency waveforms are involved, you must compensate for any time skew that occurs due to differences in signal propagation delays that occur in the voltage and current probe measurement paths. This is less of an issue at lower frequencies such as AC line voltage frequencies.

Power analyzers for power and efficiency measurements

Many power analyzers are designed specifically to provide easy and accurate efficiency measurements. These instruments typically have multiple isolated inputs to measure voltage and current simultaneously on the input and output of a power conversion device. The analyzer will multiply the voltage and current signals together and perform the integration of the resultant power waveform to accurately yield a power measurement directly in watts. It can then display efficiency directly by dividing the output power by the input power. While the bandwidth will not match that of an oscilloscope, it is usually high enough to capture the types of waveforms encountered in many applications, especially when you are analyzing 50- or 60-Hz circuits including harmonics. And power analyzers have much better measurement accuracy with up to 16-bit vertical resolution compared to 8 bits for an oscilloscope.

For example, Keysight's PA2201A IntegraVision power analyzer has all of the features necessary to accurately and easily display efficiency measurements. You can capture voltage, current, and power waveforms on each of two channels and see all six waveforms simultaneously. The IntegraVision's 5-MSample/second, 16-bit digitization captures waveforms in real time with up to 2-MHz bandwidth, providing 0.05% basic accuracy. Voltage and current inputs can float to 1,000 V above or below earth ground, eliminating the need for differential voltage probes and their associated setup complexity and measurement errors. Each channel has a voltage input, two current shunt inputs (2 Arms and 50 Arms), and a current probe input to give you the flexibility to choose your preferred method to make accurate and reliable current measurements.

Figures 4 and 5 show an example of an efficiency measurement made with the IntegraVision power analyzer on the same microinverter mentioned earlier. No differential voltage probes or current probes are needed since the inputs are floating and these power analyzers can accurately measure current directly with internal shunts. The IntegraVision screenshot shows the microinverter's voltage, current, and power waveforms on its input and output simultaneously without the need to configure any waveform math functions, as is necessary on an oscilloscope. From these waveforms, it directly calculates the efficiency shown here as 96.05 percent.

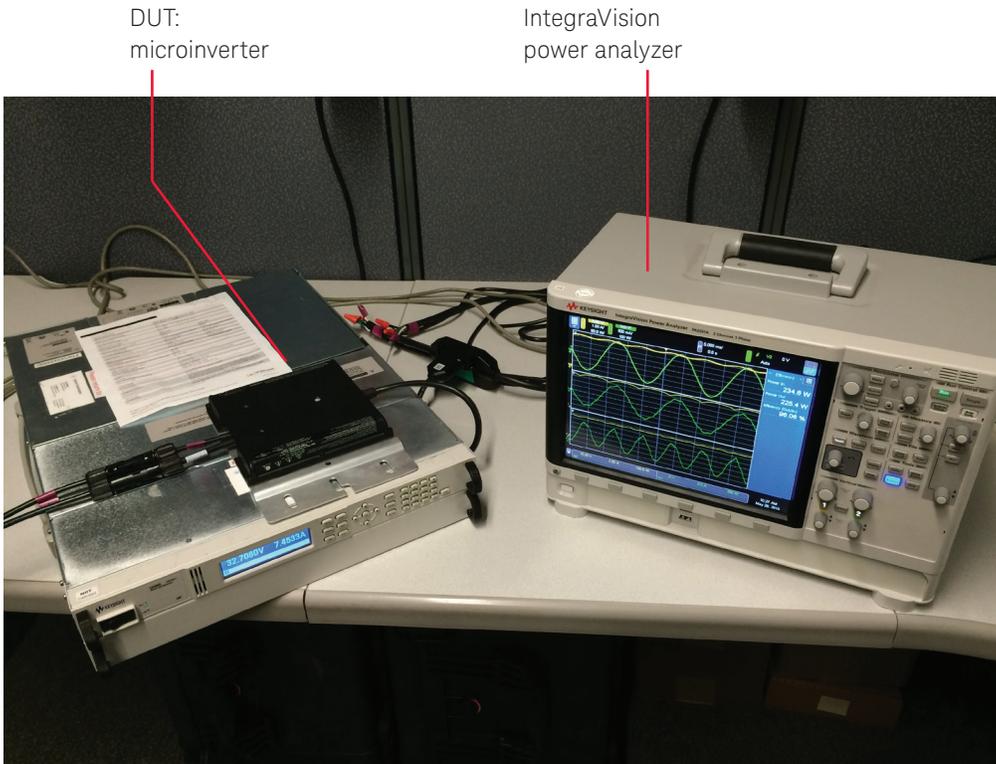


Figure 4. The Keysight PA2201A IntegraVision power analyzer shows microinverter input and output voltage, current, and power waveforms with just two channels, as each channel measures both voltage and current. It also provides built-in power and efficiency measurements that are more accurate than those calculated with a scope.

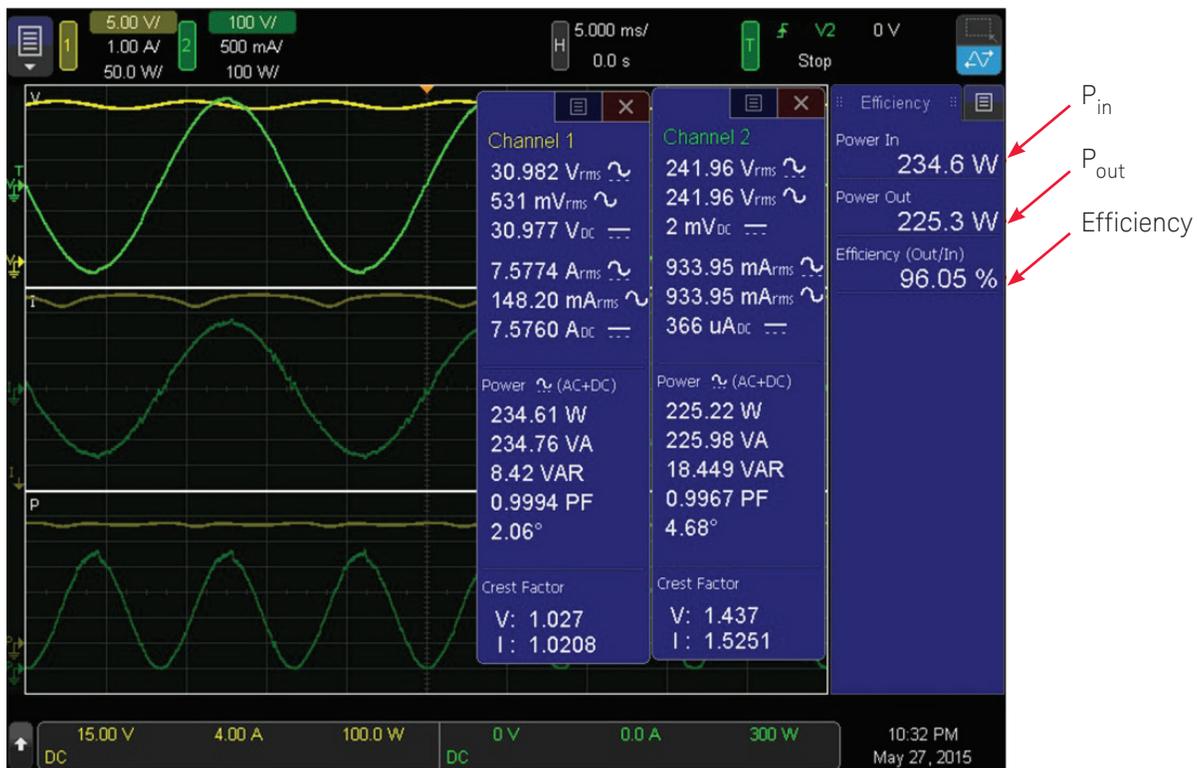


Figure 5. Close-up of IntegraVision power analyzer screenshot shows six waveforms and resultant power and efficiency measurements for this microinverter under specific operating conditions. You can also choose to display many other measured parameters.

In addition to accurate efficiency measurements, the IntegraVision power analyzer allows you to accurately measure watts, VA, VAR, power factor, crest factor, watt-hours, amp-hours, and harmonics. Figure 5 shows some of these measurements. The power analyzer also has dynamic measurement capabilities to display voltage, current, and power waveforms directly in real time enabling you to capture power disturbance waveforms such as power surges and sags, cycle dropouts, and inrush current.

Summary

In today's energy-conscious world, engineers must reduce product power consumption and improve overall product efficiency. This applies not just to conventional household appliances, but the high-power devices supporting solar grids and vehicle electrification systems. Accurate measurement of power conversion efficiency is paramount for reducing energy consumption. You can use various methods to evaluate power efficiency, each with its own set of advantages and disadvantages. You could use a multimeter, but only for DC signals, and it won't provide a direct power measurement. Oscilloscopes capture waveforms with excellent bandwidth but have limited vertical accuracy, are earth-ground referenced, and have no direct current measurement capability. A power analyzer with built-in efficiency measurement capability provides the best method for easily and accurately evaluating power consumption. It allows designers to minimize a product's energy consumption, ultimately improving the environment. Power analyzers such as Keysight's PA2201A IntegraVision easily measure power conversion efficiency. They also provide dynamic measurement capability to capture and display transient voltage, current, and power waveforms, allowing you to make all of your critical power measurements with one instrument.

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