Accurately measuring efficiency of ultralow-I_Q devices

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Introduction

While almost every power-supply engineer intimately knows and understands the lab setup for measuring efficiency, there are many important nuances that must be considered when measuring the efficiency of a device with ultralow quiescent current (I_Q). For a device that consumes less than 1 µA, the circuit's currents are very small and difficult to measure. These measurements may equate to calculated light-load efficiencies that are far lower than what is shown in the datasheet graphs and lower than what would be seen in the real application. This article reviews the basics of measuring efficiency, discusses common mistakes in measuring the light-load efficiency of ultralow-I_Q devices, and demonstrates how to overcome them in order to get accurate efficiency measurements.

Basics of measuring efficiency

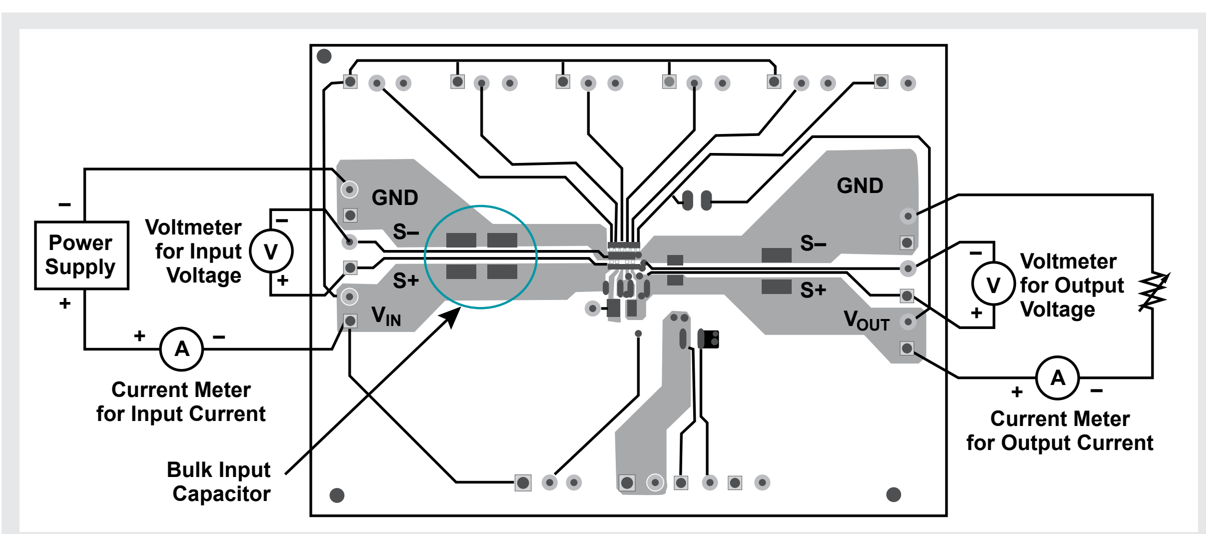
Reference 1 details the best setup to accurately measure a device's efficiency with a power-save or pulse-frequency-modulation (PFM) mode. This reference provides an excellent background to the topics covered in this article and should be read first. Generally, and especially in this article, efficiency is defined as

$$\eta\left(\text{efficiency}\right)=\frac{\text{Power}_{\text{OUT}}}{\text{Power}_{\text{IN}}}=\frac{V_{\text{OUT}}\times I_{\text{OUT}}}{V_{\text{IN}}\times I_{\text{IN}}}.$$

The following summarizes two key points made in Reference 1. The first is that any power-save mode draws relatively large bursts of current from the input supply. These bursts are an AC current from the input. Devices that always operate in continuous-conduction or pulse-width-modulation (PWM) mode draw DC currents from the input supply. Unlike the DC current drawn in PWM mode, the power-save mode's bursts of current create an incorrect RMS-current reading in the input-current meter. Therefore, the proper test setup for measuring efficiency in power-save mode includes sufficient input capacitance after the input-current meter to smooth out the AC currents drawn by the PFM mode in order to present a DC current to the current meter.

The second key point in Reference 1 regards the placement of the voltmeters relative to the current meters. It is critical in both PFM and PWM modes not to include the voltage drops across the current meters in the efficiency calculations. Therefore, each voltmeter should be connected to the input and output voltages on the PCB, ideally at the S+/S– header on most evaluation modules (EVMs). This places the input-current meter out of the circuit and the output-current meter as part of the load. These placements are shown in Figure 1 with the recommended setup for measuring PFM-mode efficiency with the best accuracy.

Figure 1. Recommended setup for measuring PFM-mode efficiency



Setup issues in measuring efficiency of an ultralow-I_Q device

Devices with an ultralow I_Q have special considerations for their efficiency-measurement setup. For simplicity, ultralow I_Q can be approximated as less than roughly 10 µA of I_Q. Below this level, the input current drawn by one or both voltmeters, as well as the leakage current of the additional input capacitor, can substantially affect the measured input current and thus the calculated light-load efficiency. Note that if higher-leakage equipment is used, these concerns also would be relevant for higher-I_Q devices. Reference 2 explains I_Q in detail.

Input resistance of the input voltmeter

In the test setup in Figure 1, the two voltmeters have some finite input resistance. For example, the standard handheld, battery-powered Fluke digital multimeter (DMM) has an input resistance of around 10 MΩ. While this certainly seems very large and unlikely to affect the efficiency measurement, calculating how much current it draws when it measures a very common 3.6-V input voltage can be revealing. In this case, when 3.6 V is applied to the DMM's terminals (across its resistance), 0.36 µA of current flows into the meter. This is effectively 360 nA of leakage current that is drawn directly from the input voltage applied to the device and flows through the input-current meter. Just attaching the input voltmeter to the circuit increases the input current by 360 nA. If the measured device has a 20-µA I_Q, then this 360 nA is less than 2% of the input current and is not very significant. But, if a step-down converter like the Texas Instruments (TI) TPS62740 with its 360-nA I_Q is being tested, then this extra current drawn by the voltmeter could be up to half of the input current. This results in quite a large difference in efficiency.

Extra load current through the output voltmeter

A voltmeter connected on the output behaves in the same way. It draws some extra (leakage) current not measured as part of the load's current. This leakage current is not included in the numerator in the efficiency calculation. The output voltmeter creates an extra load, which draws an extra (and measured) input current. With this extra unmeasured load current creating an increased input current, the measured efficiency is lower than the actual efficiency.

High leakage current of the extra input capacitor

Finally, the additional input capacitor used to smooth out the input current might have a sufficiently high leakage to draw substantial current from the input. For example, some high-capacitance capacitors have maximum leakage currents in the hundreds of microamperes. This leakage may change over time, so it should be checked before any efficiency testing. This extra current, if too high, is sure to throw off the efficiency calculations.

Solutions to measurement-setup issues

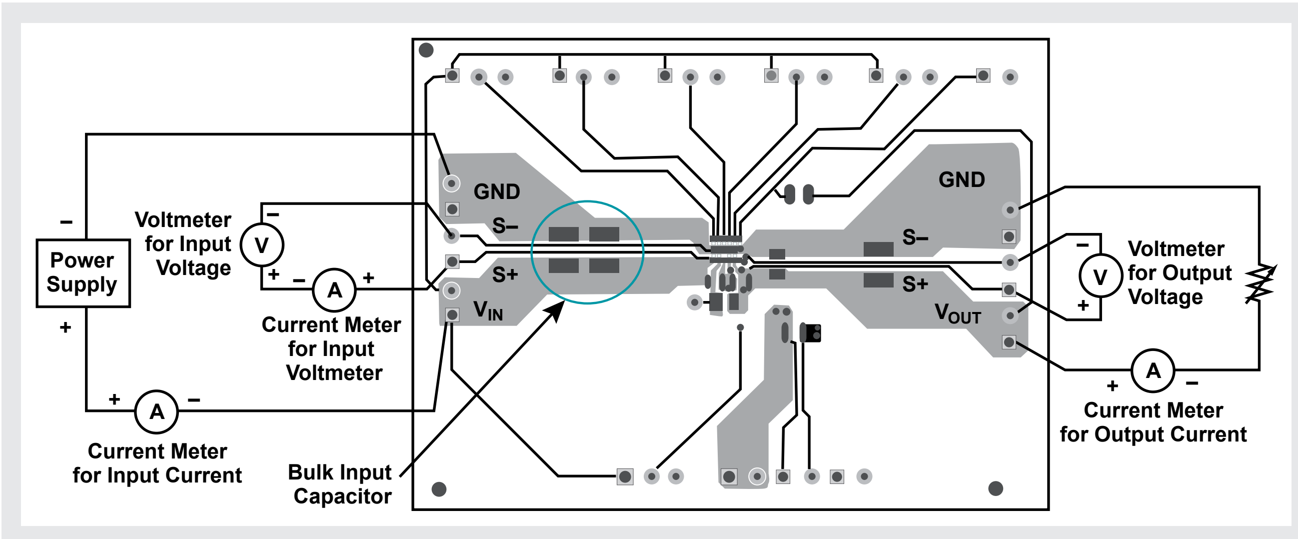
There are easy solutions to the three measurement-setup issues just described. The most important point, however, is simply to be aware that the setup used to take efficiency data can cause inaccuracies in the efficiency data collected. This is especially true at light loads, where the currents are very small and difficult to measure.

Overcoming the effects of the input voltmeter's input resistance

There are three methods of accounting for current leakage through the input voltmeter: (1) disconnecting the voltmeter, (2) connecting it in a different location, or (3) compensating for the current into it. The first and simplest method is to record the input voltage with the voltmeter connected as usual and then disconnect the voltmeter from the input terminals before recording the input current. This accurately measures the input voltage without increasing the input current. Minimal measurement inaccuracy is introduced by this method. What is not advisable is to read the input voltage from the display on the input supply (which typically is not calibrated) and use this value for the efficiency calculations. Rather, a high-quality, high-resolution voltmeter should be used to measure the input voltage at the EVM. This overcomes small voltage drops in wires and cabling between the input supply and the EVM.

The second method of accounting for the leakage current is to connect the input voltmeter in a different location. Specifically, the voltmeter's positive lead can be connected to the input-current meter's positive side, while the voltmeter's ground lead remains connected to the same location as before (the S– header on the EVM). In this way, the input voltmeter does not draw any measured current and so does not affect the calculated efficiency. The downside of this method is that the voltage drop across the input-current meter is not accounted for. At very light loads, however, such a drop is usually insignificant. To minimize this inaccuracy at heavier loads, the input voltmeter can be moved to its original location (after the input-current meter) once the measured input current is about 100 times greater than the leakage current into the voltmeter. This allows for a simple setup where the input voltmeter remains connected throughout testing and inaccurate measurement is minimized.

Figure 2. Efficiency-measurement setup to compensate for leakage into the input voltmeter



The third method of accounting for the leakage current into the input voltmeter is to measure the current through it with an additional current meter (Figure 2). The current through this new current meter is subtracted from the measured input current. The result is used to compute the efficiency. This is the most accurate way of accounting for the leakage current into the input voltmeter. The computed efficiency is highly accurate because the input voltmeter remains connected where it should be throughout the entire testing. Furthermore, assuming that the input voltage is not varied considerably throughout testing, the leakage current also remains fairly constant. This fact allows for a single measurement of the leakage current to be made at a given input voltage and for this value to be used for all data points in the efficiency testing. In other words, it is not necessary to record the data of this extra multimeter for all measurement points.

Overcoming the extra load current through the output voltmeter

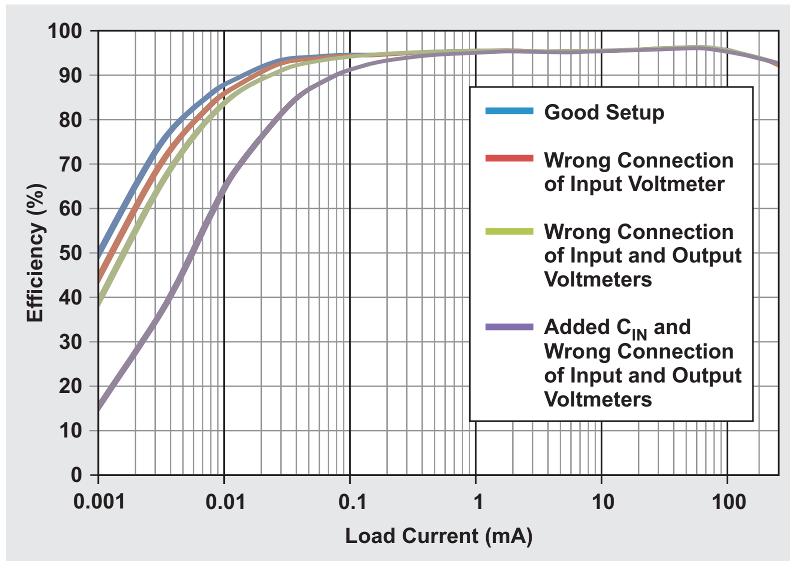
The leakage current into the output voltmeter can be accounted for in the same three ways as for the input voltmeter. The first method (disconnecting the output voltmeter) can be used in exactly the same way—connecting the voltmeter as usual, reading the output voltage, then disconnecting it and reading the input current. The second method (connecting the voltmeter in a different location) is slightly different for the output voltage. In this method, the output voltmeter should be connected after the output current meter so that its current sums with the load's current to give the total output current. Once the load current is about 100 times greater than the leakage current into the output voltmeter, the voltmeter can be moved back to its usual location on the S+/S– header. The third method (compensating for the current drawn by the voltmeter) can be used in the same way as for the input voltmeter. Note that for this method the load current used to graph the efficiency data should be the sum of the current into the load and the leakage current into the output voltmeter. Not accounting for this may slightly shift the efficiency graph on the load-current axis.

Of course, the best way to eliminate errors from leakage currents into the voltmeters is to use voltmeters with extremely low leakage currents. For example, the efficiency data in the TPS62740 datasheet[3] was taken with Agilent 34410A multimeters. Their 10-GΩ input-resistance setting was used for the voltage measurements, producing a negligible amount of leakage current with no effect on the calculated efficiency.

Minimizing leakage current from the extra input capacitor

Finally, the leakage of the input capacitor is best mitigated by choosing a proper bulk input capacitor. X5R or X7R dielectric ceramic capacitors and their inherent low-leakage currents are recommended for measuring ultralow-power efficiency, as the ceramic technology used in these capacitors produces the lowest leakage currents. If the voltage is too high for a ceramic capacitor, then a low-leakage-current polymer or tantalum capacitor should be used. It is important to consult the datasheet of the chosen capacitor to determine if its leakage might cause measurement errors. It is also important to measure the leakage current of the exact capacitor used in the efficiency testing.

Figure 3. Efficiency comparison of different test setups



Test results of efficiency-measurement setups

Figure 3 compares the measured efficiency of several different test setups that used the TPS62740EVM-186 evaluation module.[4] A proper test setup with a 100-µF ceramic bulk input capacitor was used, with compensation for the leakage current into the input and output voltmeters. This bulk input capacitance was sufficient to produce accurate results, as was evidenced by a DC input current. If longer wires from the input supply with their larger impedance had been used instead, the input-current shape might have changed to be more sinusoidal. This would have produced an inaccurate input-current reading and shows that more bulk input capacitance would have been required for an accurate measurement.

Figure 3 also shows the test results of three improper test setups: the input voltmeter's leakage not accounted for, the output voltmeter's leakage not accounted for, and an extra input capacitor with about 5 µA of leakage. For the three improper test setups, the wrong configurations build on one another; they are additive. The wrong connection of input voltmeter used the correct input capacitor as well as the correct output voltmeter. The wrong connection of input and output voltmeters used the correct input capacitor. The setup using the leaky input capacitor also used the wrong connection for the input and output voltmeters. As expected, less accurate efficiency measurements were obtained with worse test setups.

Other considerations in measuring efficiency

With an understanding of the impact that measurement setups have on measuring an ultralow-I_Q device's efficiency, there are two final considerations that deserve a mention: the remote-sense lines on the input supply, and the use of external or internal feedback resistors. Though less commonly seen, each of these has an impact on efficiency.

An input-power supply with remote-sense capability is sometimes used in efficiency-measurement test setups to provide a regulated input voltage as the load and voltage drop across the input-current meter change. However, just like the input voltmeter, these remote-sense lines draw current. In many instances, this current is relatively large—sometimes in the hundreds of microamperes. Needless to say, such high currents drawn by the test setup certainly affect the calculated efficiency and produce erroneous results. Therefore, for best results, the remote-sense lines of the input supply should be connected *before*, not after, the input-current meter.

A final consideration in measuring the efficiency of ultralow-I_Q devices is whether to use external or internal feedback resistors to set the output voltage. Most power supplies use two external resistors between the output voltage, FB pin, and ground to set the output voltage. This gives the user full flexibility to set the output voltage at any desired point. However, with external resistors and the highly sensitive external FB pin come more susceptibility to noise. Any external noise seen at the FB pin is gained up, resulting in an incorrect output voltage. To avoid this, the two feedback resistors typically should have between 1 and 10 µA of current flowing in them to keep them robust against external noise sources. Since this current is not flowing to the load, it should be considered a loss that results in decreased efficiency.

To keep efficiency high, the FB pin and two resistors should be located inside the power supply to remove them from the variable and noisy external environment. In this way, a large resistance with minimal current flow is used for the feedback resistors, and efficiency is not significantly lowered. While internal feedback resistors fix the output voltage inside the power supply and prevent the user from having every possible output voltage available, a step-down converter like the TPS62740 overcomes this limitation. It has four digital input pins that allow the user to choose from among the most common output voltages ranging from 1.8 V to 3.3 V. As well, many other TI TPS62xxx devices internally set the output voltage to be either completely fixed (as in the TPS62091) or adjustable via I^2C (as in the TPS62360). These low-I_Q devices are preferred because they do not lower the efficiency with external resistors but still allow sufficient user configurability.

Conclusion

Accurately measuring the efficiency of ultralow-I_Q devices is difficult because the currents in the circuit are very small. The basic efficiency-measurement test setup must be slightly altered to achieve accurate measurement results that reflect the capability of the real circuit in the final application. Accounting for and/or eliminating the various leakage currents in the measurement equipment is the key to an accurate measurement.

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