

Keysight Technologies

Challenges and Solutions for Power Electronics Testing Applications

Technical Overview



Introduction

The term power electronics encompasses a wide range of applications, from small power converters used in personal computers to large scale electric power generation/transmission systems. Because power electronics is essential to these functions, having robust and reliable power electronics circuits is extremely important. In addition, the need for more efficient circuits with smaller form factors continues to increase as concerns over CO₂ emissions drive the ongoing shift to alternative energy sources.

Figure 1 illustrates the broad range of power electronics applications. Many industries (such as transportation) are becoming increasingly electrified, with electronic circuits replacing older technologies such as internal combustion engines and hydraulic actuators.



Figure 1. Power electronics application overview

This technical overview provides a summary of power electronics systems, the challenges they face and the tools that power electronics engineers need to meet them. It concludes with a discussion of Keysight Technologies, Inc. solutions to these challenges.

Challenges Facing Power Electronics Applications

All power electronics applications require some sort of power conversion system. For this reason, all over the world companies are continuously working on improving the performance, efficiency, and reliability of these systems. Power conversion systems are also being used in new applications as they replace conventional systems. For instance, internal combustion engines are gradually being replaced by hybrid and electric alternatives to reduce fossil fuel consumption. Hydraulic actuators in airplanes are being replaced with electric motor based actuators to improve aircraft safety and reliability.

We will now review some typical power electronic circuit applications and discuss the challenges they face.

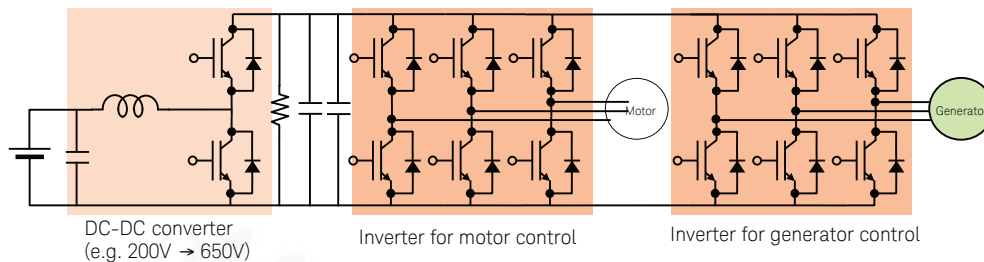


Figure 2. Block diagram of hybrid vehicle powertrain

Many modern vehicles employ hybrid powertrains to improve fuel efficiency. Hybrid systems typically have one inverter circuit for DC-DC converter electrical motor control and one for the regenerative circuit that converts kinetic energy (e.g. from braking, coasting, etc.) into electrical energy stored in the system's battery. Both of these inverter circuits use many IGBTs (Insulated Gate Bipolar Transistors), diodes, capacitors, resistors and inductors, and these components need to be able to handle very large voltages and currents. For instance, the most popular hybrid automobile today uses voltages of up to 650 V and currents of more than 200 A. Component reliability under a wide range of operating conditions (from freezing cold to hot and humid conditions) is also extremely important, since any failure could cause serious injury to the car's driver or passengers.

Component weight is another factor that affects energy efficiency because the inductors and capacitors used in the powertrain are in general large and heavy. Since higher operating frequencies allow smaller components to be used, wide band gap (WBG) devices such as SiC MOSFETs and GaN FETs (which can operate at higher frequencies than silicon devices) are gradually replacing IGBTs in switching circuits. Of course, the power devices and components used in the circuit are critical parts that cannot fail under any situation.

The second example shows the block diagram of a refrigerator compressor. It consists of an AC-DC converter and an inverter to drive the brushless DC motor. Here power consumption is the most important design factor because less power consumption means lower electricity costs for potential customers. Selecting the optimal components to be used in the circuit is critical to minimize power consumption. As in the case of the hybrid vehicle powertrain, the voltages and currents used in this circuit are relatively high (typically more than 200V and 50A).

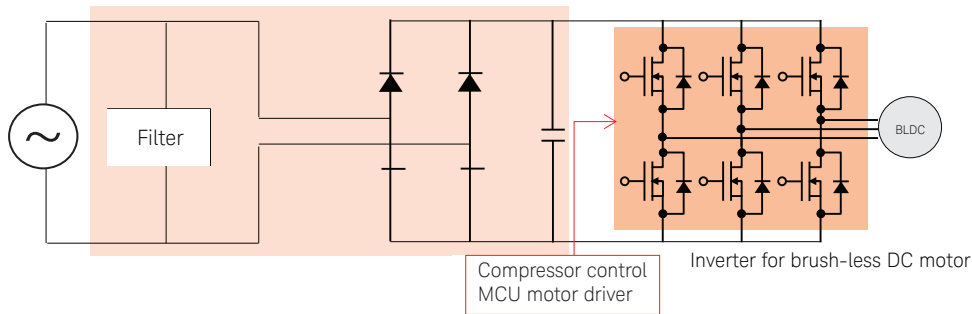


Figure 3. Block diagram of a refrigerator compressor

The third example shows the block diagram of a multi-level converter for electric energy transmission.

A multi-level converter uses many IGBTs stacked in series in order to control the extremely large voltages (e.g. 65 kV) required for power transmission. As in the case of transportation electrification, these circuits must function in both extremely cold and hot/humid environments because reliable electric power is essential to modern society. As many IGBT modules are used in parallel and series, IGBT module variation is a critical issue. If current becomes over-concentrated in one part of the circuit due to module variation then breakdown of the entire system can occur.

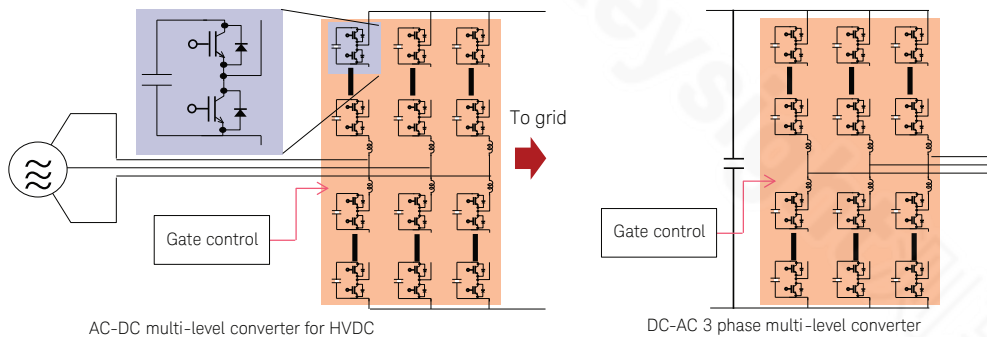


Figure 4. Block diagram of multi-level converter for grid control

The last example shows a block diagram of the DC power distribution network for a notebook PC.

PCs typically utilize many DC-DC converters to power core components (such as the CPU, memory load, HDD, etc.). While the voltages and currents are not as large as in the previously discussed examples, the current densities can be quite high and power loss has to be minimized to increase battery life. For these reasons, many PC manufacturers are beginning to use WBG devices in their products.

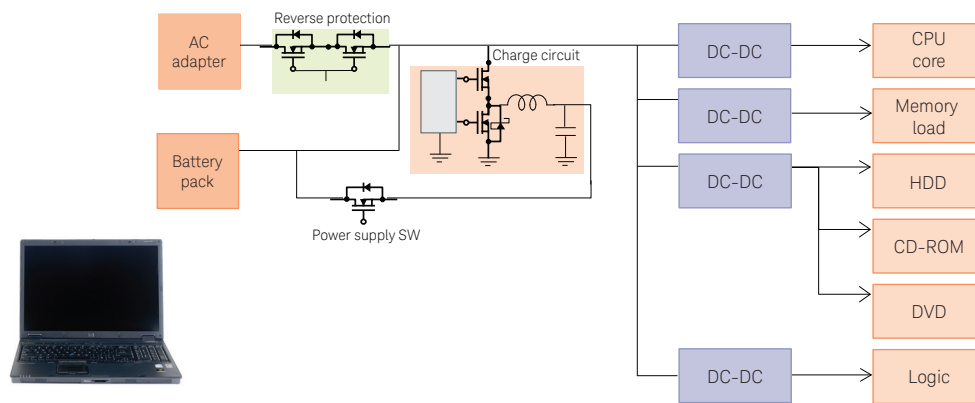


Figure 5. Block diagram of DC power distribution in notebook PC

Another big issue for power electronics products is the widespread prevalence of counterfeit components. The chance of purchasing counterfeit or substandard power devices or components is higher than for low-power semiconductor devices because many power device suppliers purchase components from trading inventory, and counterfeit components are common in such inventory.

In summary, power electronics circuit designers face many challenges.

- Many applications are mission critical and cannot fail under any circumstances
- Power circuits must function at both low and high temperatures
- Power circuit components operate at high currents/voltages and high power densities
- High overall energy efficiency is desired and critical
- Higher power converter operating frequencies are necessary to create lighter and smaller modules
- Counterfeit components are a much bigger concern as compared to low-power components

What Should Power Circuit Designers Do?

Power electronics engineers have to develop highly efficient, safe and reliable electric circuits, so the evaluation of final circuit characteristics is very important. It is therefore mandatory to evaluate the efficiency of the entire circuit, including verifying current and voltage waveforms at each circuit node. To achieve this, a detailed understanding of the power devices and components used in the circuit is necessary. This is especially true for the power devices (such as IGBTs and MOSFETs) used in the circuit, since their performance often dictates the efficiency, safety and reliability of the entire circuit. Unfortunately, device manufacturer datasheet information is often insufficient to meet these needs. The datasheet conditions are often different from actual use conditions, and the supplied information often has large margins with no information on device variation. This makes it hard to design reliable and efficient circuits using only the information supplied by the device and component manufacturers.

What Should Power Component Manufacturers Do?

Due to the increasing use of WBG devices, the demand for greater energy efficiency and the need for improved reliability and safety, power device and component manufacturers need to understand that the information they have previously been providing power circuit designers is no longer sufficient. In addition to conventional parameters and characteristics curves under typical conditions, power electronics circuit designers need component data taken under many different operating temperatures, voltages and currents. Moreover, in addition to IV parameters other device characteristics such as gate charge (Q_g) and FET junction capacitances (C_{iss} , C_{oss} , C_{rss}) are also now very important.

Providing more detailed characterization information to power electronics circuit designers and engineers is essential to remaining competitive in the marketplace.

Test Challenges

Based on the previous discussion, the following summarizes the major challenges facing power electronics circuit testing.

- Testing under actual operating conditions (e.g. potential surge current, frequency, voltage, etc.)
- Ensuring operation across a wide temperature range
- Measuring the device parameters critical to power loss efficiency calculations
- Identifying counterfeit components with unconventional test methods
- Ensuring stable DC-DC converter operation regardless of load or input change
- Testing enough devices and components to gain a statistical understanding of true device performance
- Ensuring frequency harmonics do not adversely impact circuit performance
- Complying with international standards (e.g. JDEC, LV, JEITA, etc.)

There are two main phases in power electronics testing. The first phase is power component level testing and the second phase is power converter/inverter level testing. The following sections describe the Keysight solutions available to test both of these phases.

Keysight solutions for power component test

Figure 6 shows the wide variety of solutions that Keysight Technologies provides for component level test.

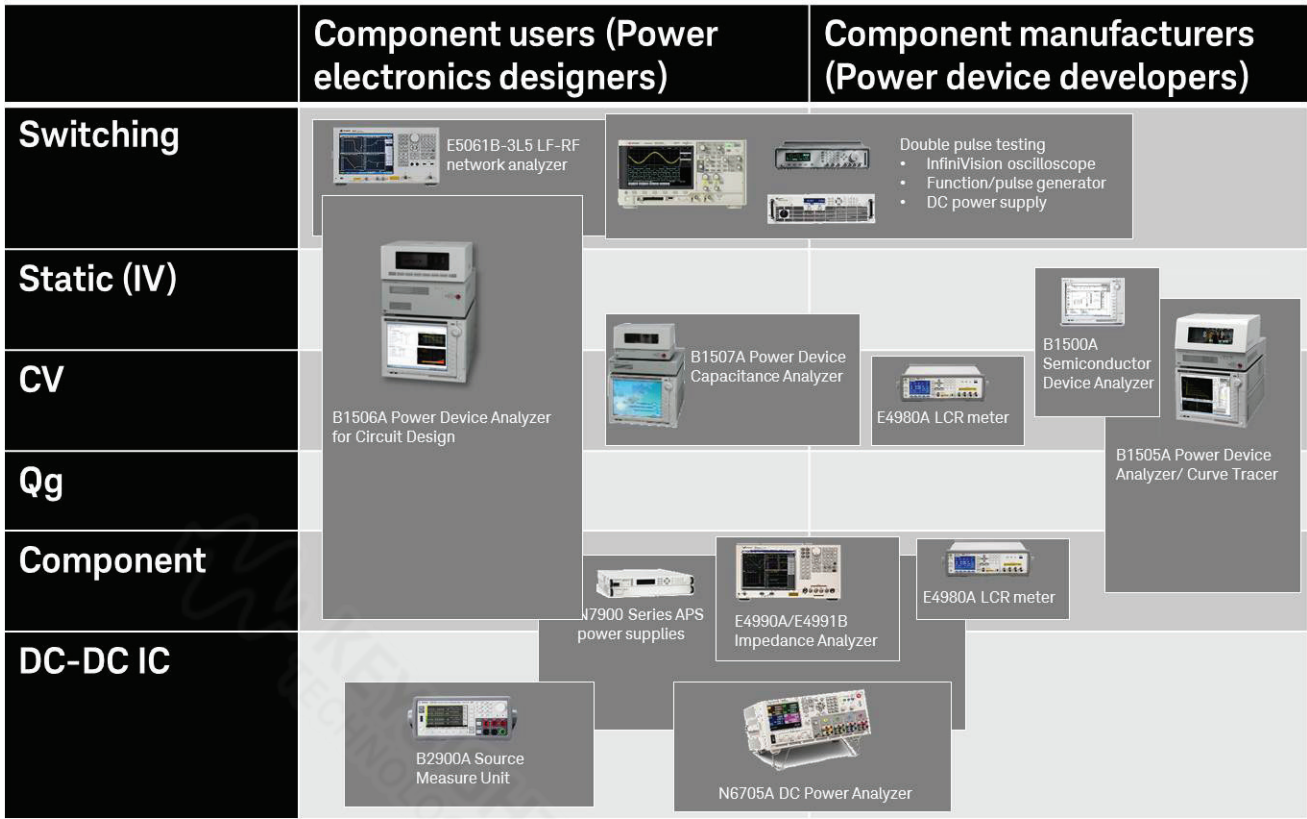


Figure 6. Block diagram of DC power distribution in notebook PC

The next section describes each solution for component level testing in detail and gives additional information on Keysight Power Device Analyzers, which are all-in-one solutions for power device and component level testing.

B1506A Power Device Analyzer for Circuit Design

The B1506A Power Device Analyzer for Circuit Design is a complete solution that can help power electronics engineers maximize the efficiency, safety and reliability of their products. It can evaluate all relevant device and component parameters under a wide range of operating conditions, including IV parameters such as breakdown voltage and on-resistance, as well as three-terminal FET capacitances, gate resistance, gate charge and power loss.

Characterizing devices under actual operating conditions

The B1506A covers a wide range of current and voltage, from sub-nA to 1500 A and microvolts to 3 kV. This supports the evaluation of the vast majority of devices and components used in power electronics circuits. The B1506A's 50 μ s pulse width measurement capability limits self-heating effects and provides more accurate device characterization data. Moreover, the B1506A can also evaluate device capacitance, gate resistance and gate charge characteristics – all key parameters for determining device power loss. Figure 7 shows some typical device parameters obtained using the B1506A.

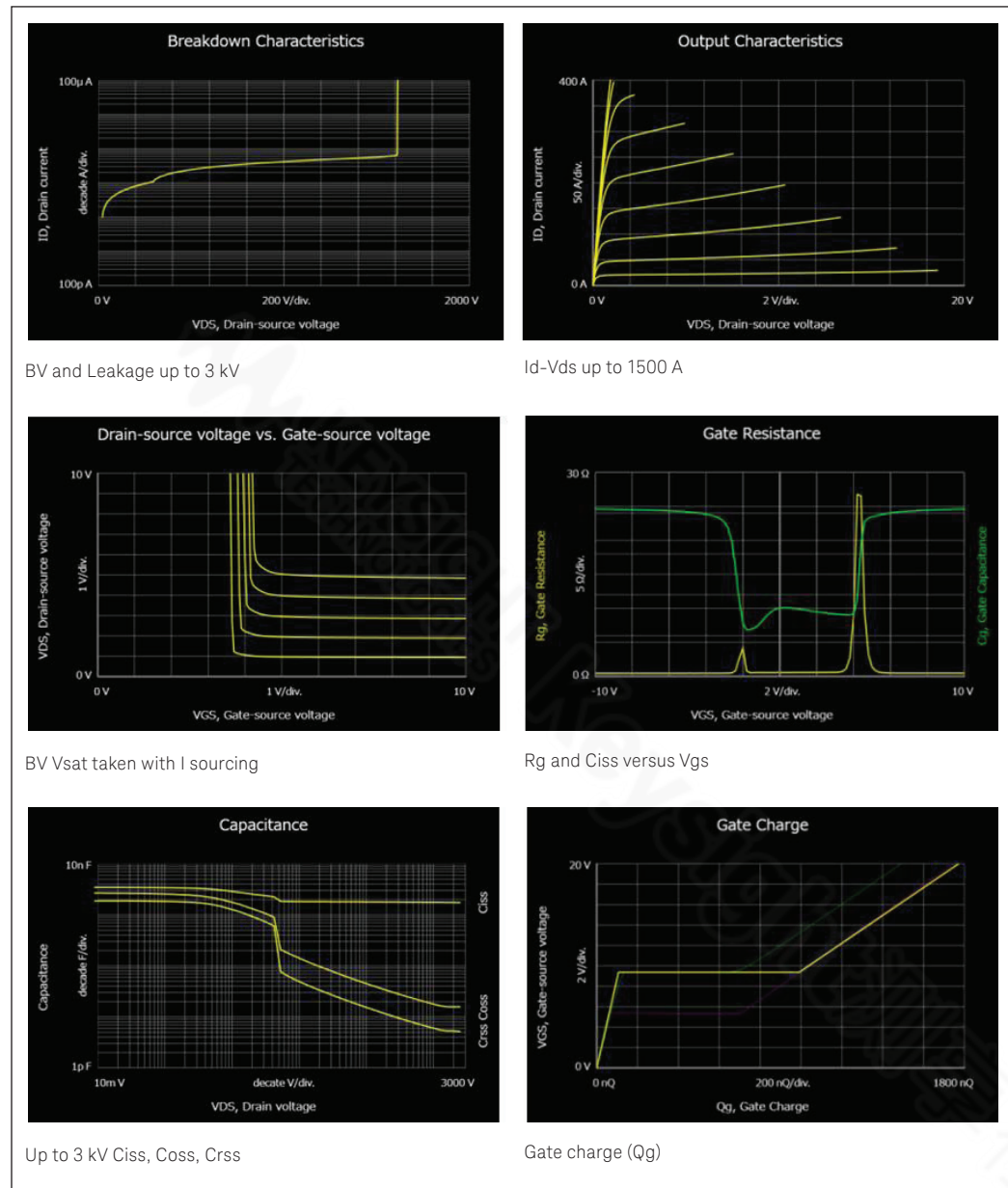


Figure 7. Typical characteristics measured by B1506A

The SMU (Source Measure Unit) architecture is the core technology for the B1506A as well as the other device analyzers described later. It has a wide range of current and voltage sourcing/measuring capabilities, provides unparalleled accuracy and allows you to specify current or voltage limits. All of these are essential for power device characterization.

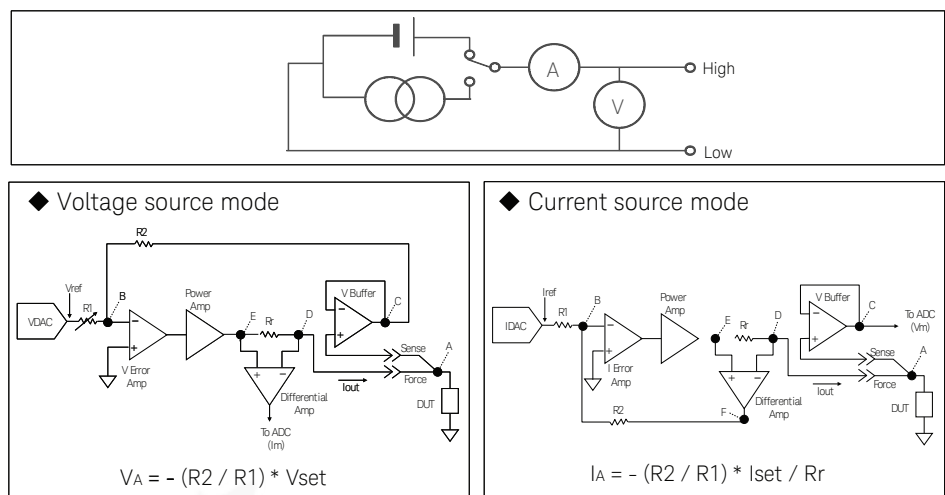


Figure 8. SMU Technology

Verifying device operation across temperature

Characterizing device behavior across temperature is important for power electronics applications, but it is not easy to do. Temperature test chambers can be slow to stabilize, and the long cables from the test equipment to the chamber introduce resistance and inductance that can cause oscillation issues. In contrast, the B1506A provides auto-
mated, easy to use and accurate temperature dependent measurement across a wide range of temperature (from -50 °C to +250 °C). Two solutions are available. One solution supports industry-standard inTEST Thermostream temperature systems, while the other solution is a thermal plate (also available from inTEST) that resides inside the B1506A's test fixture (see Figure 9). With these solutions, thermal testing that used to take an entire day can be done in less than one hour (refer to Figure 10).

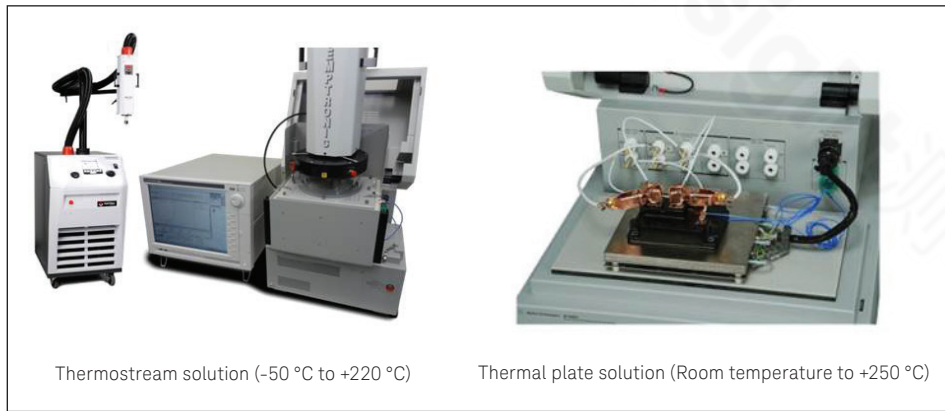


Figure 9. Temperature testing solutions supported by the B1506A.

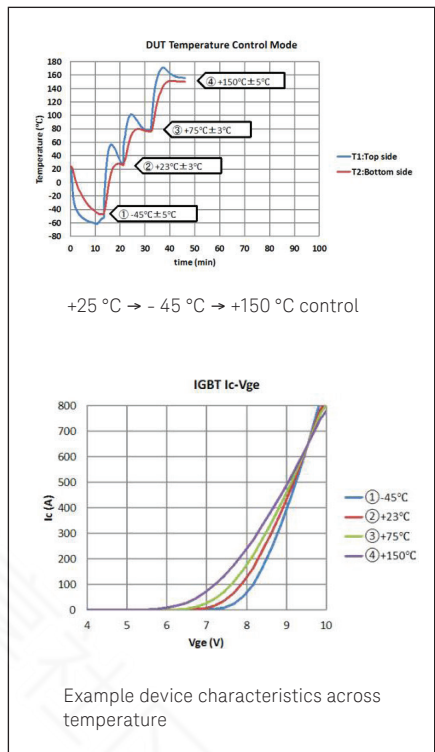


Figure 10. Examples of temperature dependent measurements made using the B1506A

Maximizing circuit efficiency through optimal device selection

Maximizing circuit performance and efficiency requires more data than conventional curve tracers can supply. In particular, as switching frequencies increase switching loss and drive loss begin to dominate device power loss. This makes characterization of device capacitances, gate resistance and gate charge extremely important. However, since these parameters are difficult to measure many power electronics engineers do not attempt them. The B1506A solves this issue with its ability to not only automatically measure all of these parameters, but also with its capability to use the extracted parameters to perform power loss calculations.

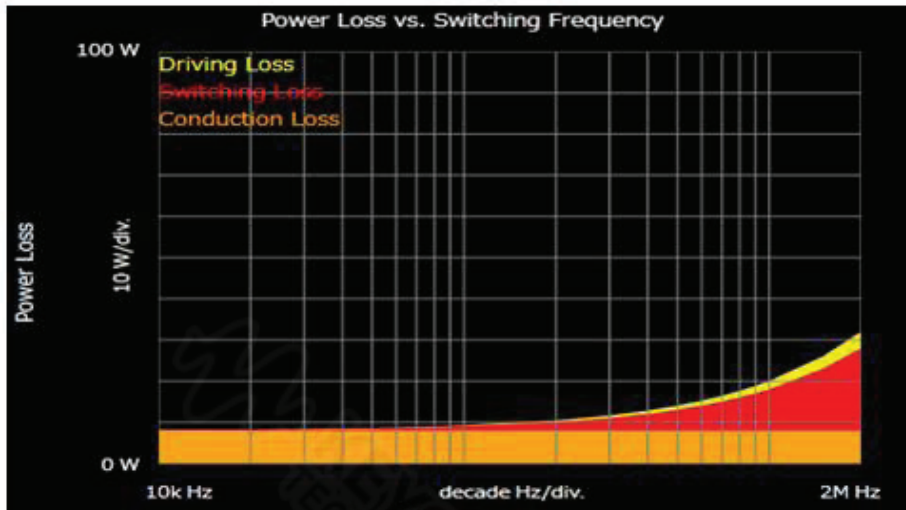


Figure 11. Calculated power loss vs. frequency made using the B1506A

Intuitive and automated datasheet characterization

The B1506A's datasheet characterization mode enables anyone to automatically measure key device parameters without any specialized training. All characteristics can be printed out in datasheet format, making it easy to compare the performance of different components.

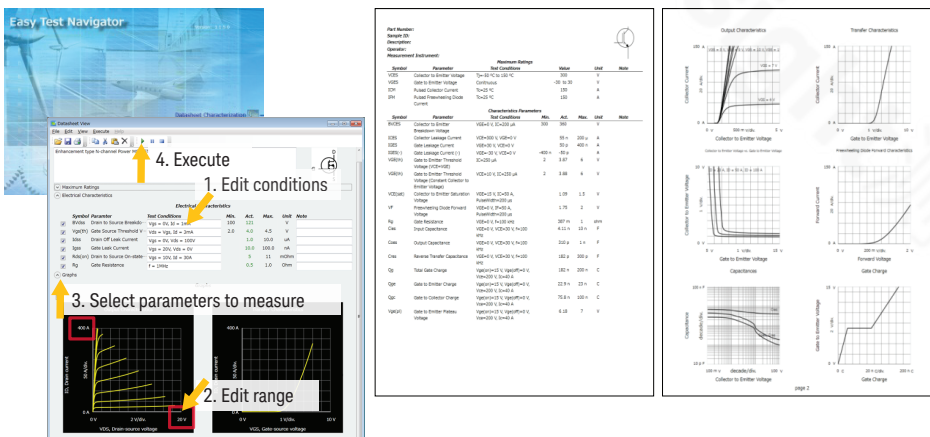


Figure 12. Easy Test Navigator software provides intuitive and automated device and component testing with datasheet generation capabilities

B1507A Power Device Capacitance Analyzer

If you already have a conventional curve tracer or production power device tester for DC characterization but lack capacitance measurement capability, then the B1507A can bridge this gap in your testing resources. It provides automatic transistor input, output and reverse transfer capacitance measurement capability at high voltage bias (up to 3 kV), as well as the ability to measure gate resistance. In addition, the abilities to measure breakdown voltage up to 3 kV and to accurately characterize leakage currents down to the sub-pA level can reveal device characteristics that conventional test equipment (such as curve tracers) cannot detect. These features are also effective to detect counterfeit or substandard power devices.

The B1507A supports both package device testing and on-wafer device testing. Therefore, it supports the needs of power electronics circuit designers, incoming inspection engineers, failure analysis engineers and power semiconductor device engineers.



B1505A Power Device Analyzer/Curve Tracer

The B1505A is a more flexible alternative to the B1506A that offers wider current and voltage ranges (up to 10 kV), better low-current measurement accuracy, high voltage with medium current measurement (e.g. 500 mA at 1.2 kV) capability, a GaN current collapse testing option and the ability to measure more than three pins simultaneously. The B1505A can also measure both on-wafer and packaged devices. Besides being widely used by power device manufacturers, the B1505A is valuable for power electronics engineers utilizing GaN power devices, measuring the sense emitter current of 4-terminal IGBTs, and characterizing HVICs for gate driver circuits.



B1500A Semiconductor Device Analyzer

The B1500A is the de-facto standard instrument used by small signal semiconductor device engineers and manufacturers to analyze device characteristics and improve the device manufacturing process. It supports all aspects of measurement, such as fundamental current-voltage (IV), capacitance-voltage (CV) and QSCV (Quasi-Static Capacitance-Voltage) measurement with uncompromised measurement reliability and repeatability. In addition, B1500A supports a unique Waveform Generator/Fast Measurement Unit (WGFMU) module that contains an arbitrary waveform generator (AWG). The WGFMU module can create arbitrary voltage signals while simultaneously performing fast sampling measurements at a 200MSa/s sampling rate (5ns interval). The WGFMU module can reveal the dynamic characteristics of devices under various types of stress, perform ultra-low signal measurements, and make transient measurements. The B1500A's fast current measurement and QSCV measurement capabilities are useful in the initial phases of power device development, since they can help evaluate common WBG device concerns such as interface states and oxide reliability. The B1500A's ten-slot modular architecture allows you to add or upgrade measurement modules if your measurement needs change over time.



Power device switching characterization

Switching characteristics are an important part of component level test, and Keysight has both oscilloscopes and pulse generators that can help evaluate these parameters.

The InfiniVision 3000/4000/6000 X series oscilloscopes provide good bandwidth and resolution at a reasonable cost, and they support both current and voltage probes. The 81110A pulse generator is also able to provide voltage pulses fast and large enough to characterize automotive components.

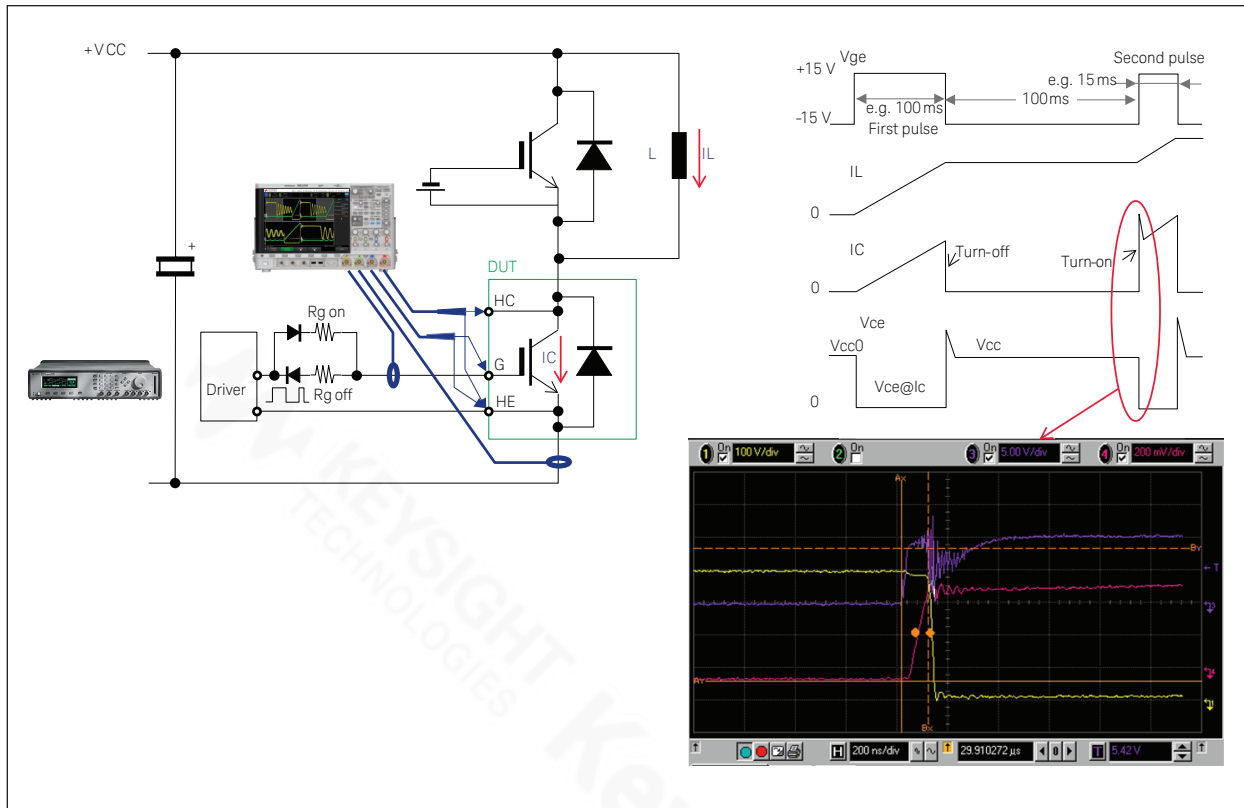


Figure 13. Double pulse test circuit with Oscilloscope and pulse generator

Various component testing (L, C, R, resonator, MEMS)

Power components such as inductors, capacitors, resistors, resonators and MEMS sensors are important power electronics circuit components. Some of them can be tested using the B1506A Power Device Analyzer. If characterization at frequencies higher than 1 MHz is necessary or components such as resonators need to be evaluated, then the E4990A or E4991B Impedance Analyzers are the best choices. They are industry standard instruments for impedance measurement and they provide unparalleled accuracy with real world characterization under various operating conditions. Measurement frequencies for the E4990A and E4991A go up to 30 MHz and 1 GHz (respectively). The E4991B Option 007 also provides a simple temperature characterization environment.

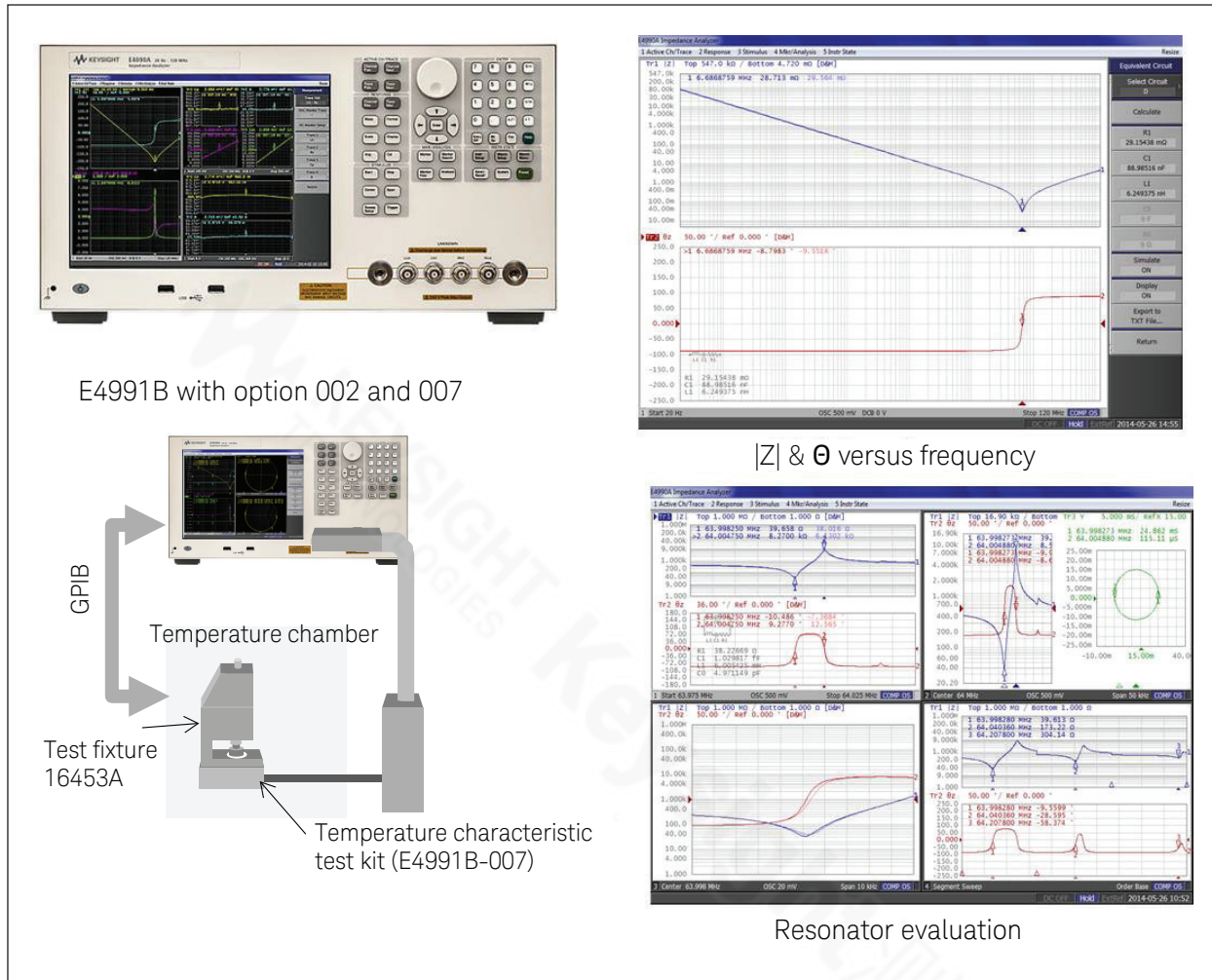


Figure 14. E4990A/E4991A component characterization examples including thermal characterization set up

Battery testing

Conventional battery charging and discharging test uses a switch to transition from charging to discharging. However, this method introduces timing delays which are not present under real world operating conditions. Moreover, if a diode is used in the switching circuit then the power supply has to be quite large in order to supply sufficient current.

The N7900 Series of dynamic DC Power Supplies and the N7909 Power Dissipater Units solve this issue by being able to both source and sink current. In other words, the same port can act as both a DC source and an electric load so that the transition between these two functions is seamless. Therefore, this solution is much better at simulating the real world operations of charging and discharging. In addition, an 18-bit equivalent digitizer allows accurate characterization including internal resistance calculations, which are not possible using conventional methods due to their insufficient voltage measurement accuracy.



Figure 15. N7900 Series Power Supplies with N7909 provides seamless transition between DC source and electric load.

DC-DC Converter IC evaluation

A benchtop SMU with two channels can simplify the otherwise complicated test setup necessary to perform DC-DC converter characterization. Figure 16 shows two test set ups for DC-DC converter IC load regulation evaluation; the first uses 2 digital multimeters, 2 DC voltage sources and a load resistor while the second uses a 2-channel SMU. Figure 16 also shows example measurement results and a test circuit block diagram.

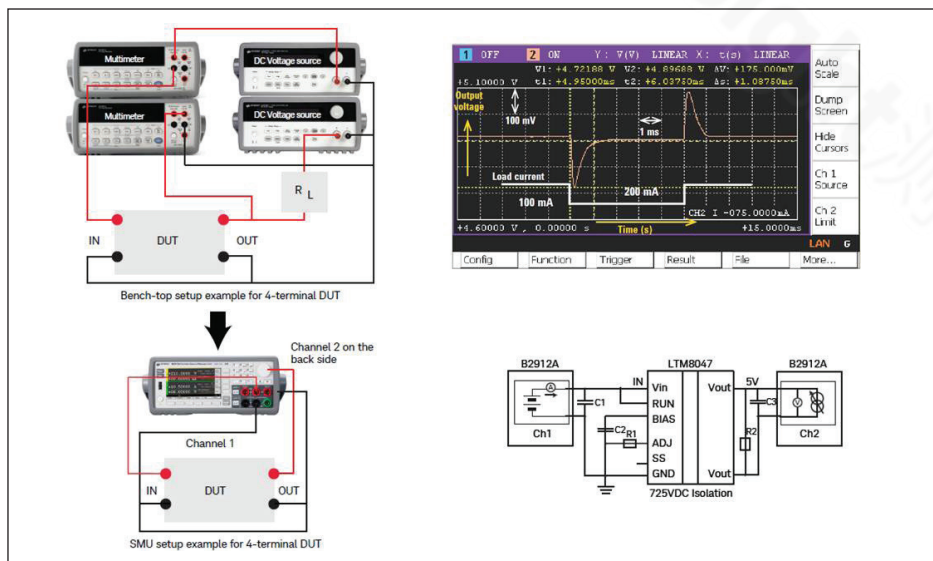


Figure 16. Simplified test setup using a 2-channel SMU and corresponding DC-DC converter test results

Figure 17 shows the variety of products that Keysight offers that are capable of doing DC-DC converter evaluation across a wide range of currents and voltages.



Figure 17. Keysight products for DC-DC converter evaluation

Keysight solution for inverter/converter test

In addition to components, Keysight also provides solutions to characterize the inverters and converters that constitute the basic building blocks of power electronics. Since an efficient power conversion circuit is essential, being able to evaluate the entire inverter/converter circuit is also necessary to optimize performance. In addition, inverter/converter circuits must be stable and reliable and meet Electromagnetic Interference (EMI) specifications.

The following chart shows Keysight’s solution portfolio.

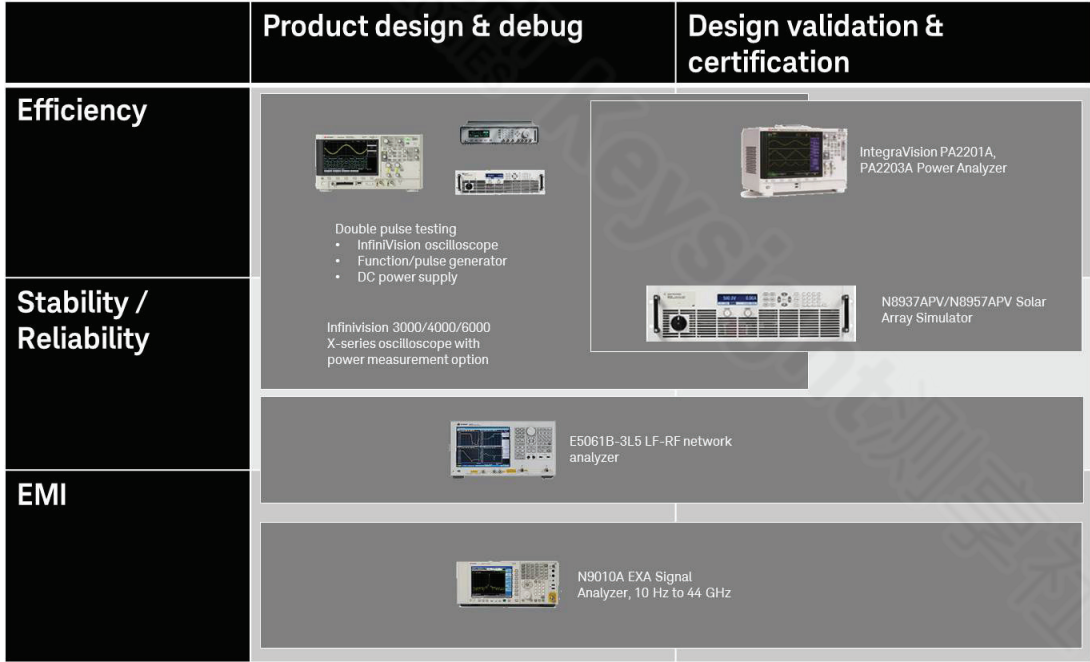


Figure 18. Keysight solution portfolio for power electronics inverter/converter testing

For EMI testing, signal and spectrum analyzers are useful tools to detect signals at unexpected frequencies emanating from a circuit board. If such signals are detected then corrective actions (such as increasing the shielding) can be performed. The next section explains each solution for inverter/converter testing (except EMI testing) shown in Figure 18 in greater detail.

Evaluating inverter/converter operation

The Keysight InfiniVision 3000/4000/6000 X-series of oscilloscopes with the power measurement option has the ability to analyze many power analysis parameters, including current harmonics, inrush current, switching loss, slew rate, modulation, output ripple, turn on/turn off, transient response, PSRR, and efficiency.

In the initial product development phase, having the ability to measure these key parameters and check their behavior at each node is very important. Therefore, an oscilloscope combined with the appropriate pulse sources and power supplies creates a very effective tool to evaluate inverter/converter functionality.

Evaluating power efficiency

For validating the power efficiency of a power electronics circuit, the Keysight PA2201A IntegraVision power analyzer is an excellent choice. You can capture voltage, current, and power waveforms on each of the PA2201A's two channels, and you can view all six of these waveforms simultaneously with 5-MS/second sampling, 16-bit digitization, 2-MHz bandwidth and 0.05% basic accuracy. Voltage and current inputs can also float up to 1000 V above or below earth ground, thereby eliminating the need for differential voltage probes with their associated setup complexity and measurement error. Each channel has one voltage input, two current shunt inputs (2 Arms and 50 Arms), and one current probe input to give you maximum flexibility to choose your preferred method to make accurate and reliable current measurements.

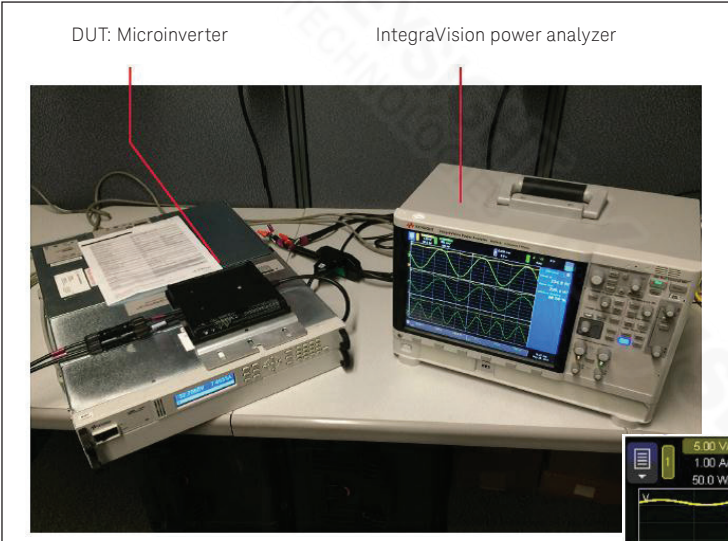


Figure 19. Power efficiency measurement using the PA2201A IntegraVision power analyzer

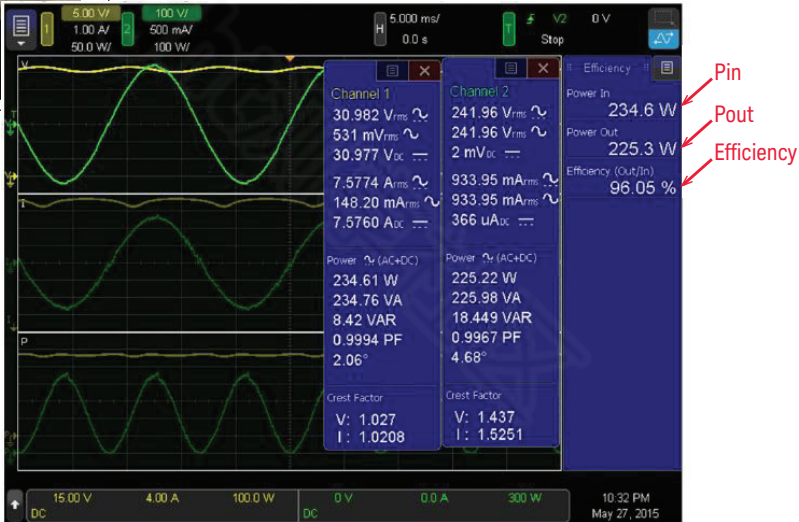


Figure 20. Power analyzer screenshot showing six waveforms and accompanying power and efficiency measurements.

DC-DC Converter loop gain evaluation

To enable a DC-DC converter to respond quickly to the load variations of modern high-speed LSIs, it is important to optimize the balance of response speed and stability within the feedback circuits.

DC-DC converter loop gain is a good indicator of the DC-DC converter's voltage regulation stability. Loop gain's amplitude and phase characteristics across frequency show its stability and responsiveness. Phase margin, which is the difference between the phase angle of the loop gain and zero degrees, and gain margin, which is the difference between the loop gain's amplitude and zero dB at the frequency at which the phase angle is zero degrees, are key parameters for loop gain stability. Crossover frequency, which is defined as a frequency where the loop gain is equal to one ($= 0$ dB), shows the response speed to load variations.

The E5061B-3L5 LF-RF ENA Series Network Analyzer can evaluate all of the key parameters and characteristics listed above.

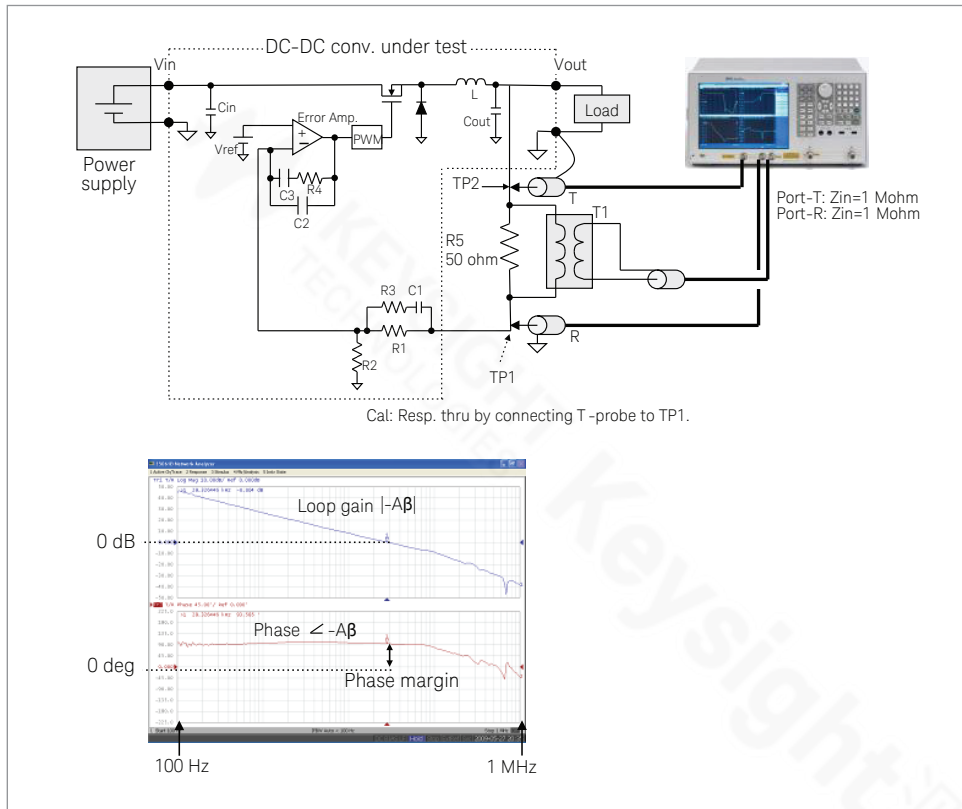


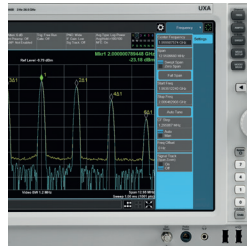
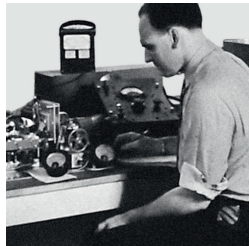
Figure 21. Loop gain measurement example set up results using E5061B-3L5

Summary

The continuing expansion of solid-state power electronics into more applications has created many challenges for power electronics engineers and power device/component engineers. The goals of improved operating efficiency and increased safety also require that power electronics circuits and their components undergo much more extensive testing than they did in the past. As shown in this document, Keysight Technologies provides a variety of solutions that cover both traditional and leading-edge power electronics testing needs.

From Hewlett-Packard through Agilent to Keysight

For more than 75 years, we've been helping you unlock measurement insights. Our unique combination of hardware, software and people can help you reach your next breakthrough. **Unlocking measurement insights since 1939.**



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