Application Note

High Amplitude Arbitrary/Function Generator Simplifies Measurement in Automotive, Semiconductor, Scientific and Industrial Applications

Tektronix®

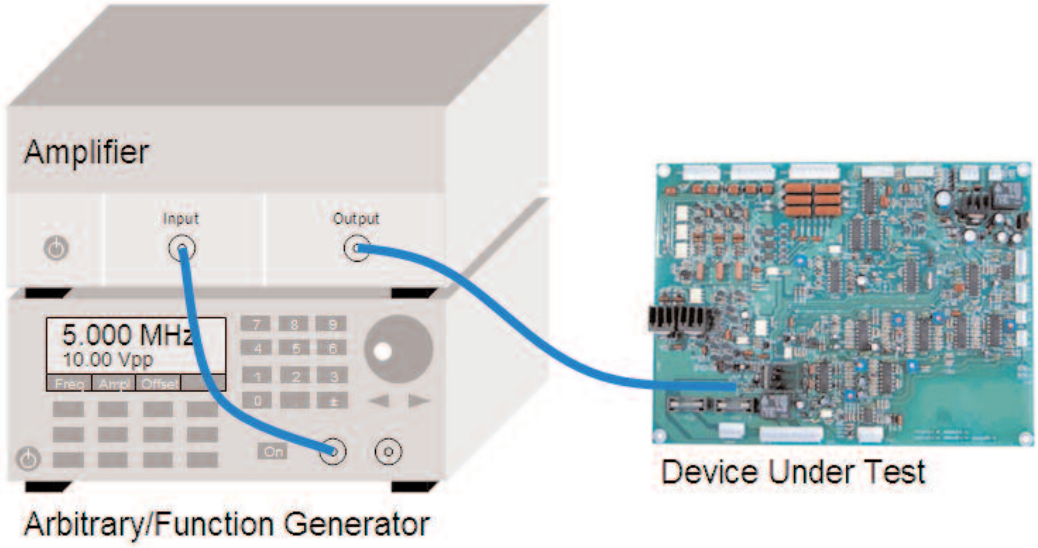


Figure 1. Measurement setup with external amplifier.

A number of electronic design applications require stimuli with amplitudes that exceed the capabilities of most arbitrary/function generators available in the market today. These applications include power semiconductors, such as MOSFETs and IGBTs widely used in automotive electronic systems and switching power supplies, amplifiers for gas chromatography and mass spectroscopy detectors, and others in science and industry.

Commonly, arbitrary/function generators provide amplitudes of up to 10 V_{pp} into 50 Ω loads and 20 V_{pp} into open circuits. The devices mentioned above often operate over an input range that is twice as large. Until now, testing these devices over their full operating range commonly required an amplifier to boost the signal provided by a standard generator. This increased the complexity of the test set-up, created uncertainty about the effective amplitude at the amplifier output, and added equipment cost.

This application note describes the conventional approach of generating high amplitude signals with an external amplifier. It then discusses typical applications and shows the benefits of using a novel arbitrary/function generator with integrated high amplitude stage. Applications described in this note include measuring the timing and switching characteristics of power semiconductors for automotive applications and the characterization of amplifiers for gas chromatography detectors.

The Conventional Approach

Figure 1 shows the typical measurement setup of a standard arbitrary/function generator with additional amplifier to boost the amplitude to the required level. The generator output is connected to the amplifier input. Some amplifiers allow the inputs and/or outputs to be configured to match different source and/or load impedances. Commonly, boost amplifiers do not feature a display so that the effective output amplitude must be monitored with an oscilloscope or other measurement device. This adds to the complexity of the measurement setup and requires additional time, especially when amplitude levels need to be adjusted and verified before and during the test.

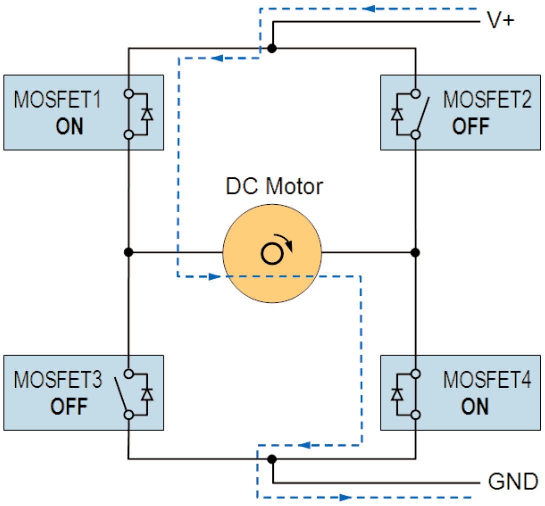


Figure 2. H-bridge configuration of four MOSFETs in a DC-motor drive.

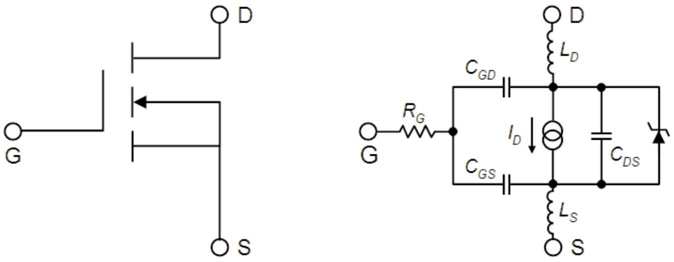


Figure 3. MOSFET schematic and equivalent circuit.

Measuring Switching Time on Power MOSFETs

Power MOSFETs are used in a variety of automotive motion control, power management, and climate control applications. They drive small motors, solenoids, anti-lock brake, electrical power steering and electronic stability program systems as well as ignitor circuits for H.I.D lamps. They are also a key component of integrated starter/alternators.

Figure 2 shows an example of MOSFETs used in an H-bridge topology to drive a DC motor. This configuration provides forward, reverse and braking functions.

When used as a switch, the MOSFET's basic function is to control the drain current via the gate signal. In these applications, switching time is an important criteria considered by circuit designers during the component selection. A MOSFET’s switching performance is determined by the time required to establish voltage changes across its internal capacitances (see Figure 3). Note that the gate-to-source voltage must first charge the MOSFET’s input capacitance to its characteristic threshold level before drain current conduction can start.

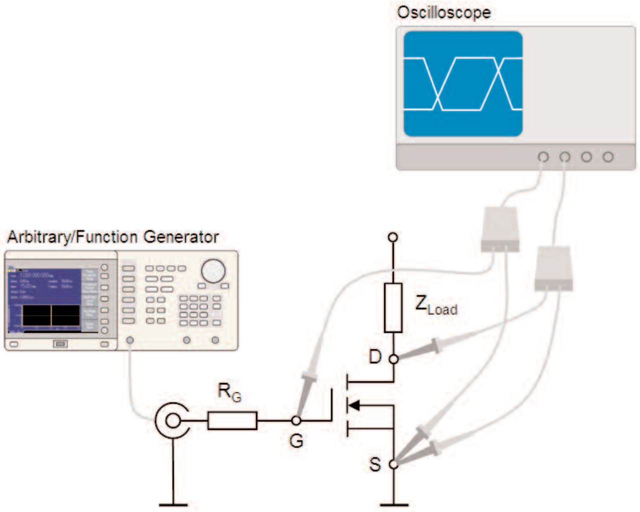


Figure 4. Setup for measuring switching time of a power MOSFET.

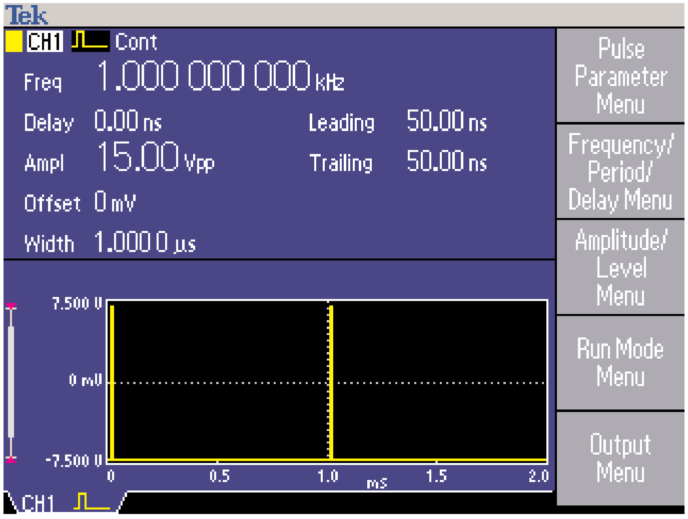

Tek
CH1 Cont
Freq 1.000 000 000 kHz
Delay 0.00 ns
Leading 50.00 ns
Ampl 15.00 Vpp
Trailing 50.00 ns
Offset 0 mV
Width 1.0000 µs

Figure 5. The AFG3011 shows the amplitude directly on the display.

Time related parameters of interest are turn-on and turn-off delay, as well as rise and fall time. To measure these parameters, the MOSFET's gate is stimulated with a narrow pulse from the signal generator input. The gate and drain voltages are measured with an oscilloscope (see Figure 4).

Using an arbitrary/function generator with integrated high amplitude output stage instead of an external amplifier gives the user direct visibility of the effective signal amplitude at the MOSFET's input circuit without the need to measure it with an oscilloscope.

The turn-on delay can now be determined conveniently via cursor measurements on the trace displayed on the oscilloscope screen. Turn-on delay is the time it takes from the moment the gate-to-source voltage reaches 10% of its final value until the drain-to-source voltage declines to 90% of its initial value. Similarly, turn-off delay is the time taken from the moment the gate-to-source voltage declines to 90% of its previous level until the drain-to-source voltage has risen to 10% of the supply voltage. For the measurement of the drain signal's rise and fall times, modern oscilloscopes offer convenient automated measurements.

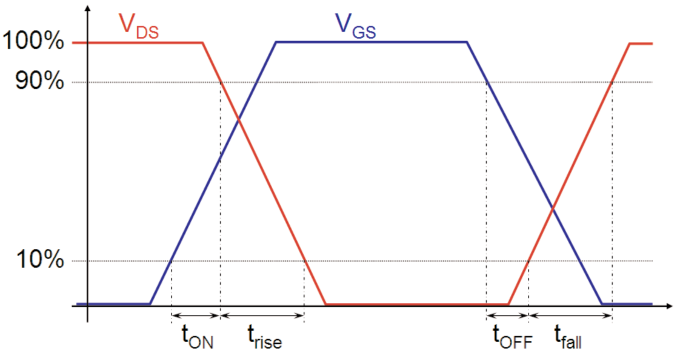


Figure 6. Measuring switching time of a power MOSFET.

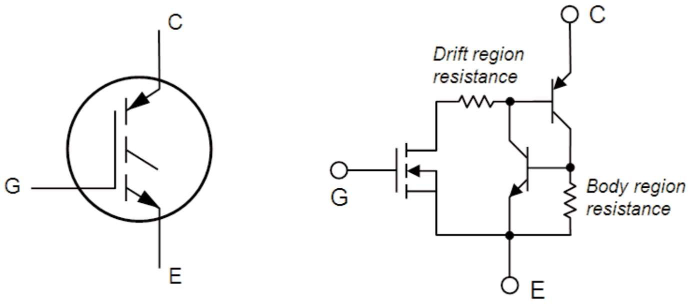


Figure 7. IGBT circuit symbol and equivalent circuit.

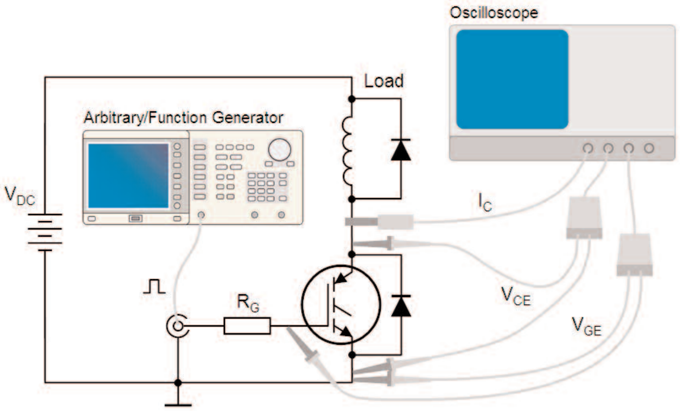


Figure 8. IGBT gate drive circuitry and switching test circuit.

Analyzing the Switching Waveforms of an IGBT

In recent years, insulated gate bipolar transistors (IGBTs) have been finding increasing use in industrial and automotive applications as replacement of MOSFETs thanks to their high switching speed, high current capabilities, large blocking voltages, and simple gate drive characteristics, but lower conduction losses and lower voltage drop in the on-state.

Industrial applications for IGBTs include traction, variable speed motor drives, uninterrupted power supplies (UPS), induction heating, welding, and high-frequency switch mode power supplies in telecom and server systems. In the automotive industry, IGBTs are in huge demand for ignition coil driver circuits, motor controllers, and safety related systems.

IGBTs are a cross between bipolar transistors and MOSFETs. In terms of output switching and conduction characteristics, the IGBT resembles the bipolar transistor. However, while bipolar transistors are current controlled, IGBTs are voltage controlled like a MOSFET. To assure full saturation and limit short circuit current, a gate drive voltage of +15V is recommended.

Like a MOSFET, an IGBT has capacitances between gate, emitter, and collector. When voltage is applied between the gate and emitter terminals, the input capacitance is charged up through the gate resistor R_G in an exponential fashion until the IGBT's characteristic threshold voltage is reached where collector-to-emitter conduction is established. Likewise, the input gate-to-emitter capacitance must be discharged to a specific plateau voltage, before collector-to-emitter conduction is interrupted, and the IGBT turns off.

The size of the gate resistor significantly impacts the dynamic turn on and turn off characteristics of the IGBT. A smaller gate resistor charges and discharges the IGBT's gate-to-emitter capacitance faster, resulting in short switching times and small switching losses. However, a small gate resistor value can also cause oscillations due to the gate-to-emitter capacitance of the IGBT and parasitic inductance of the leads. To reduce turn-off losses and to improve the IGBT's immunity to noise injected through the rate of change of the collector-to-emitter voltage which can be substantial for inductive loads, it is recommended that the gate drive circuitry includes substantial on and off biasing.

The IGBT's best performance varies by application, and the gate drive circuit must be designed accordingly. In hard-switching applications such as motor drives or uninterrupted power supplies, the gate drive parameters must be selected so that the switching waveform does not exceed the IGBT's safe operating area. This can imply a sacrifice in switching speed at the expense of switching loss. In soft-switching applications where the switching waveform is well within the safe operating area, the gate drive can be designed for short switching times and lower switching loss.

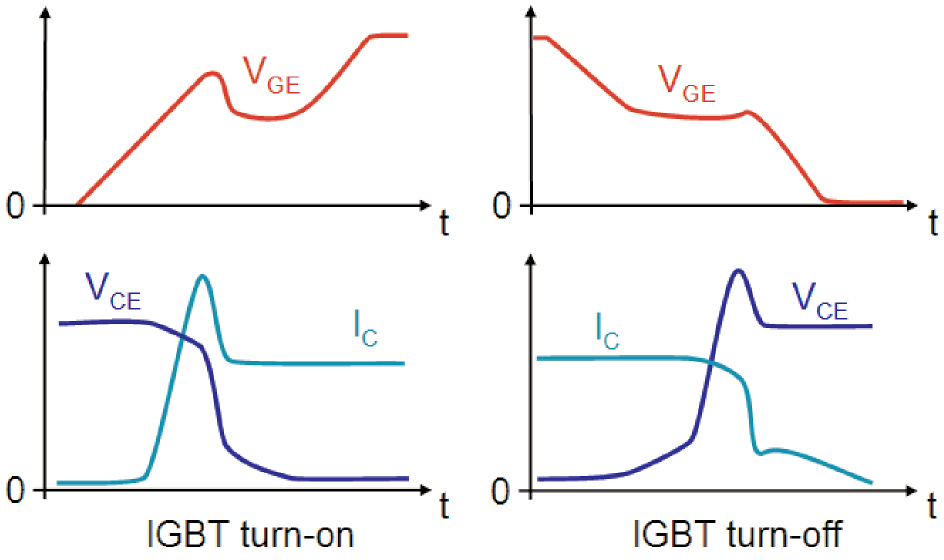


Figure 9. Switching waveforms of an IGBT.

To optimize the design of an IGBT gate drive, the design engineer must understand the device's switching characteristics under the actual load conditions. To analyze these switching characteristics, the gate of the IGBT is stimulated with a series of single pulses while the gate-to-emitter voltage, collector-to-emitter voltage and collector current are measured with an oscilloscope. Thanks to its capability to generate pulses with high amplitudes, the arbitrary/function generator AFG3011 is ideally suited for this task. Since the IGBT's collector-to-emitter voltage has a very high dynamic range for inductive loads, the measurement requires a high-voltage differential probe. The gate-to-emitter voltage can be measured with a standard passive probe, and the collector current with a non-intrusive current probe.

Figure 9 shows the typical switching waveforms of an IGBT with inductive load. From these waveforms, the design engineer can determine the switching energy, on-state losses and whether the IGBT is operating within the safe operating area. Based on the measurement data, the engineer can then determine whether the selected pulse repetition frequency, amplitude and edge transitions are adequate to achieve the design objectives. If adjustments are necessary, dedicated short-cut keys on the AFG3011 front panel provide direct access to all pulse parameters. They can then be conveniently modified via rotary knob or numerical keys free from timing glitches and without interrupting the test.

A variety of factors must be considered during the measurement, such as the propagation delay (skew), offset and noise inherent to the probes. The engineer will find it beneficial to use an oscilloscope with a software tool that takes care of the probe related issues, automatically calculates the switching power losses, and determines the safe operating area of the IGBT.

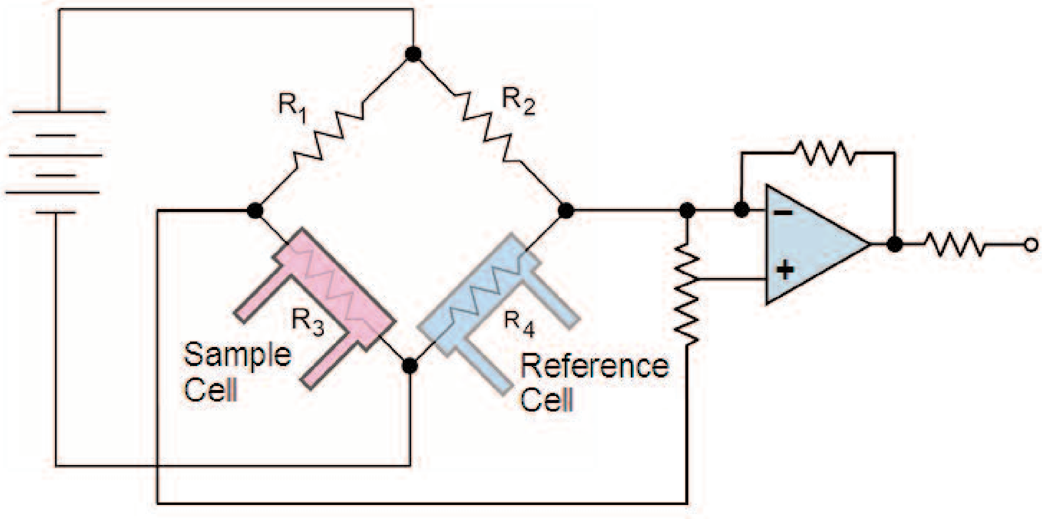


Figure 10. Thermal Conductivity Detector and Wheatstone bridge.

Characterization of Gas Chromatography Amplifiers

Gas chromatography is a technique for separating and analyzing the existence and concentration of chemicals in a complex sample. It involves the analyte being vaporized and injected into a continuous flow of an inert carrier gas, most commonly helium for its high thermal conduction. To detect the characteristics of the sample in the carrier gas, various detector types are available, each with particular advantages and disadvantages.

One of the most common types of gas chromatography detectors is the Thermal Conductivity Detector (TCD). Although more sensitive and specialized detectors are available, TCDs continue to be popular due to their simple construction, ruggedness, versatility, sensitivity, linearity, and low cost.

A TCD consists of a sample cell and a reference cell. The sample cell is used for characterizing the analyte. The reference cell contains only carrier gas. Each cell contains a heated element positioned in the flow path of the gas and is temperature controlled. Measurements with a TCD are made by measuring changes of the heated elements' resistance caused by temperature variations during the flow of the analyte gas.

The heated elements are either filaments or thermistors. The resistance of filaments increases with temperature (positive coefficient of resistance), and the resistance of thermistors decreases with rising temperature (negative coefficient of resistance). The choice of heating element depends on the temperature inside the cell and properties of the measured substance.

When only carrier gas is present in the cells, thermal energy flows at a stable rate from the heated element to the detector body. When an analyte is introduced into the sample cell, the thermal conductivity inside the cell changes, the heated element warms up and changes its resistance. The heated elements of sample and reference cell are often incorporated into the arms of a Wheatstone bridge circuit (see Figure 10). In this configuration, variations in resistance of the heated element inside the sample cell changes the output voltage of the bridge.

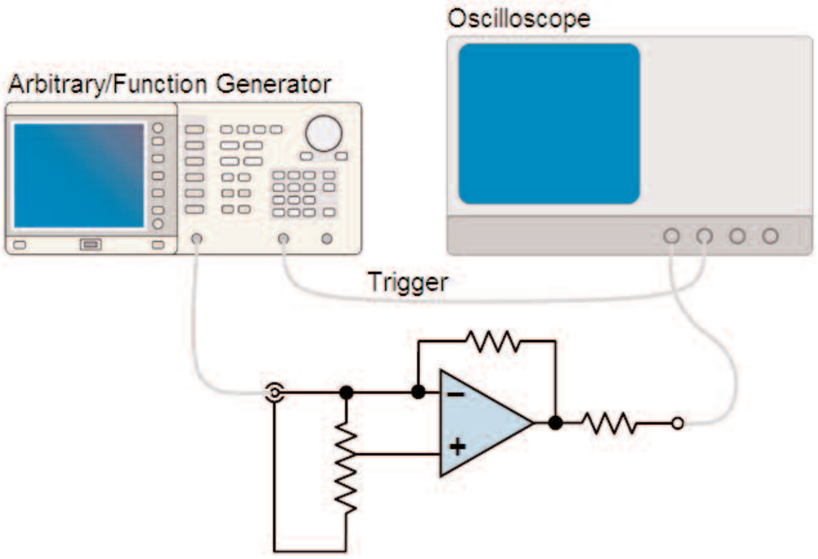


Figure 11. Measurement set-up to characterize amplifier.

The sensitivity of the TCD depends on the current flow through the heated elements and the temperature inside the cells. Higher currents increase the voltage change across the measurement bridge and result in higher temperatures, but can also shorten the filament life. These trade-offs need to be factored in when laying out the electrical design. In practice, the output voltage of the bridge is typically between 15 V and 20 V.

The output of the measurement bridge is connected to an amplifier. A resistor network at the amplifier input enables the selection of different sensitivity ranges. At the amplifier output, an analog-to-digital converter samples the signal and converts it into digital form for processing by a digital processor.

The designer of the measurement amplifier needs to characterize the amplifier for its bandwidth, slew rate, step response, linearity and dynamic range. This requires a variety of input signals of different wave shapes, frequencies and amplitudes. It would be impractical to generate all these input signals via actual measurements with the TCD. Using a modern arbitrary/function generator to simulate the signal from the Wheatstone bridge is much more convenient and offers more flexibility. Figure 11 shows the measurement setup. An oscilloscope measures the amplifier output.

If the output of the arbitrary/function generator is limited to maximum amplitudes of 10 V_{pp} into 50 Ohm, a separate amplifier is required to boost the signal level to the 15 to 20 V typically delivered by the Wheatstone bridge. Using an arbitrary/function generator like the Tektronix AFG3011 that is capable of delivering these high amplitude levels directly simplifies the measurement setup. It also gives the user direct visibility and control over the effective amplitude of the test signal that feeds into the amplifier.

Signal Amplitude and Load Impedance

The output voltage delivered by a signal generator depends on the impedance of the connected load or device under test. The reason for this lies in the output impedance of the generator. As an example, Figure x shows the equivalent output circuit of the AFG3011. Depending on the amplitude setting, the instrument delivers a certain current I. If a load Z_{DUT} of 50 Ω is connected to the generator output, half of I flows through the generator's output impedance Z_{OUT} and the other half through Z_{DUT}. If Z_{DUT} has an impedance that is significantly larger than Z_{OUT}, then almost all of I flows through Z_{OUT}, resulting in almost twice the output voltage compared to 50 Ω loads.

Specification sheets for arbitrary/function generators typically state the maximum output amplitudes for 50 Ω and for high impedance loads. The output amplitude of the AFG3011, for example, is specified as 20 V_{pp} for 50 Ω loads, and 40 V_{pp} into open circuits. For other load impedance values, the maximum output voltage can be calculated with the following formula:

$$\text{Max } U_{OUT} = \frac{40\ V_{pp}}{1 + \frac{50\ \Omega}{Z_{DUT}}}$$

In their standard setting, arbitrary/function generators are commonly configured for a load impedance of 50 Ω. For other load impedances, the impedance value can be configured into the instrument to enable the display of the correct amplitude and offset values. In the AFG3000 Series, the load impedance setting is made in the Output Menu, which becomes accessible after pressing the desired function button, e.g "Sine".

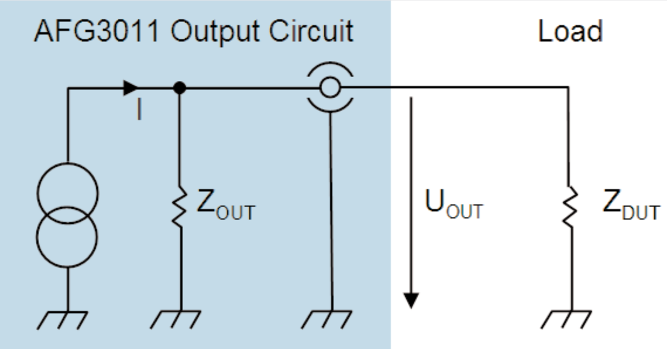
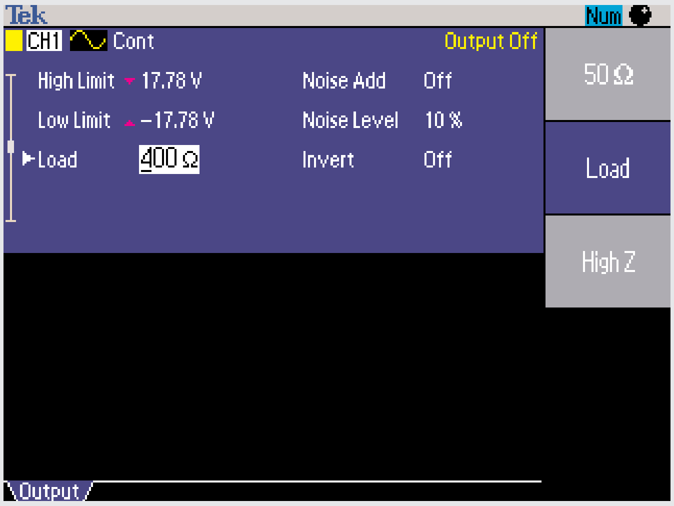


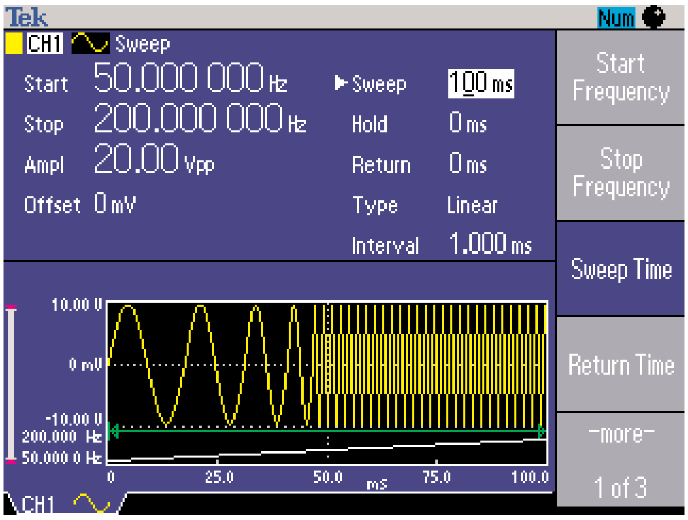
Figure x. Equivalent Output Circuit of AFG3011.



High Limit 17.78 V
Low Limit −17.78 V
Load 400 Ω
Noise Add Off
Noise Level 10 %
Invert Off

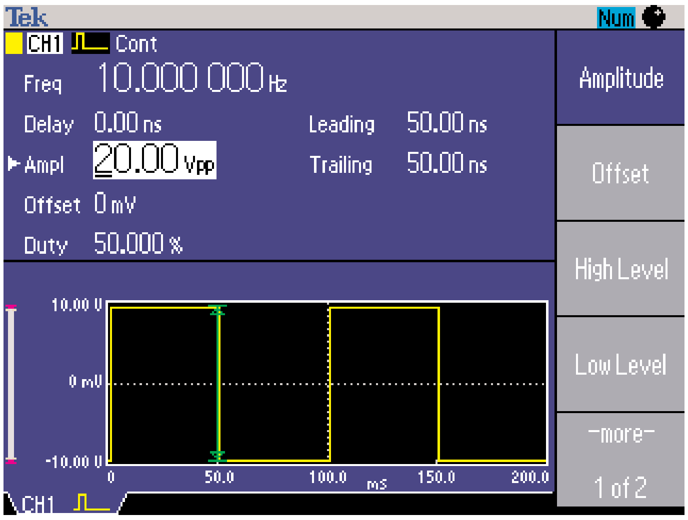
Figure y. Load Impedance Selection on the AFG3000 Series.

Please note that the load impedance setting does neither change the generator's output impedance nor the load impedance itself. It merely impacts the amplitude and offset display, and ensures that the instrument displays the correct values of the effective amplitude across the connected load.



CH1 Sweep
Start 50.000 000 Hz
Stop 200.000 000 Hz
Ampl 20.00 Vpp
Offset 0 mV
▶Sweep 100 ms
Hold 0 ms
Return 0 ms
Type Linear
Interval 1.000 ms
200.000 Hz
50.000 0 Hz

Figure 12. AFG3011 Sweep Mode Display.



CH1 Cont
Freq 10.000 000 Hz
Delay 0.00 ns
▶Ampl 20.00 Vpp
Offset 0 mV
Duty 50.000 %
Leading 50.00 ns
Trailing 50.00 ns

Figure 13. AFG3011 Pulse Mode Display.

To measure the bandwidth of the amplifier, configure the function generator in sweep mode, select amplitude, start and stop frequencies, as well as the sweep time according to your design specifications. The Tektronix AFG3011 allows convenient access to these parameters via designated short-cut keys on the front panel, and top level screen menu selections. The large display of the generator shows all relevant settings including the amplitude and a graphical representation of the waveform at a single glance, providing full confidence in the instrument settings. An oscilloscope that is triggered by the generator at each start of the sweep traces the amplifier response.

On the measurement trace on the oscilloscope screen, use a horizontal marker to find the -3 dB amplitude level which is equivalent to 70.71% of the peak value. Then, while observing the measurement trace on the oscilloscope screen, narrow the sweep range by adjusting start and stop frequencies on the signal generator until the measurement trace starts at the lower bandwidth limit and ends at the upper bandwidth limit. The amplifier bandwidth can then be determined by reading the last settings of start and stop frequencies on the signal generator.

As another measurement example, let us consider the determination of the amplifier's rise time. The latter provides a measure of the amplifier's capability to detect narrow peaks in the measurement signal from the TCD as they are generated by trace amounts of the sample in the carrier gas. The measurement setup is the same as depicted in Figure 11, except that the trigger line is not required. The arbitrary/function generator is configured to generate pulses. Modern digital oscilloscopes measure the step response of the amplifier and provide a direct reading of the signal rise and fall time via automated measurements.

Conclusion

Modern arbitrary/function generators like the AFG3011 allow the generation of signal amplitudes up to 20 Vpp into 50 Ohm loads directly without the use of an external boost amplifier. This simplifies the test set-up and reduces equipment cost in many applications. It also saves measurement time, because the generator shows the effective amplitude directly on its display, making a separate measurement with a voltmeter redundant.

Beyond the test applications described in this note, high-amplitude arbitrary/function generators are also used for the testing of displays, MEMS technology, solenoids as well as for mass spectrometry and related scientific applications.

Contact Tektronix:

ASEAN / Australasia (65) 6356 3900
Austria +41 52 675 3777
Balkan, Israel, South Africa and other ISE Countries +41 52 675 3777
Belgium 07 81 60166
Brazil & South America (11) 40669400
Canada 1 (800) 661-5625
Central East Europe, Ukraine and the Baltics +41 52 675 3777
Central Europe & Greece +41 52 675 3777
Denmark +45 80 88 1401
Finland +41 52 675 3777
France +33 (0) 1 69 86 81 81
Germany +49 (221) 94 77 400
Hong Kong (852) 2585-6688
India (91) 80-22275577
Italy +39 (02) 25086 1
Japan 81 (3) 6714-3010
Luxembourg +44 (0) 1344 392400
Mexico, Central America & Caribbean 52 (55) 5424700
Middle East, Asia and North Africa +41 52 675 3777
The Netherlands 090 02 021797
Norway 800 16098
People's Republic of China 86 (10) 6235 1230
Poland +41 52 675 3777
Portugal 80 08 12370
Republic of Korea 82 (2) 6917-5000
Russia & CIS +7 (495) 7484900
South Africa +27 11 206 8360
Spain (+34) 901 988 054
Sweden 020 08 80371
Switzerland +41 52 675 3777
Taiwan 886 (2) 2722-9622
United Kingdom & Eire +44 (0) 1344 392400
USA 1 (800) 426-2200
For other areas contact Tektronix, Inc. at: 1 (503) 627-7111
Updated 17 October 2007

For Further Information
Tektronix maintains a comprehensive, constantly expanding collection of application notes, technical briefs and other resources to help engineers working on the cutting edge of technology. Please visit www.tektronix.com

04/08 FLG/WOW 75W-21998-0

Tektronix®
Enabling Innovation