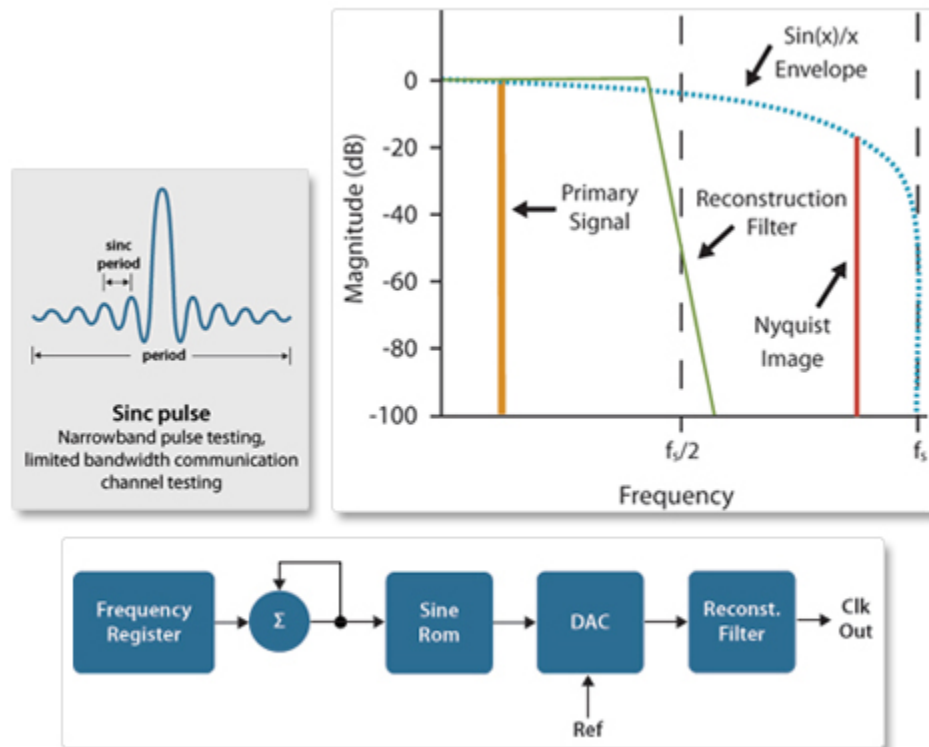


# Waveform Generator Fundamentals

Test equipment applications require signal stimuli varying from advanced communication signals to the playback of captured real-world analog signals. Signal source instruments generate the signal stimulus that is applied to a device under test (DUT). Consequently, signal sources comprise an important class of test instruments. This article describes applications of an arbitrary waveform generator as a general purpose function generator and waveform generator.



Although the terminology for the different classes of signal sources is not standardized, there is a general market consensus on the naming conventions for signal, function and waveform generators. A signal generator provides a high-fidelity sine wave signal ranging from low frequencies to many GHz. Attenuation, modulation, and sweeping are typical features of a signal generator. A function generator is a lower-frequency instrument that provides sine, square, pulse, triangle and ramp waveforms. Function generators provide these standard functions from DC to a few MHz, and typically provide large voltage ranges. An arbitrary waveform generator (AWG) is a highly flexible signal source that generates any arbitrary waveform that has been constructed point-by-point in digital memory. The constructed waveform is converted to an analog signal using a digital-to-analog converter (DAC) operating at clock rates up to a few GHz. An arbitrary waveform generator can also substitute as a conventional function generator by using on-instrument algorithms to generate standard functions. This paper describes the characteristics and applications of arbitrary waveform generators.

# Arbitrary Waveform Generator Output Signal Types

The variety of waveforms that may be synthesized with an AWG can be broadly categorized into four categories: standard functions, advanced functions, arbitrary waveforms, and waveform sequences.

## Standard Functions

Standard functions include the sine, square, pulse, triangle, and ramp waveforms that are commonly used in applications such as the testing of baseband, audio, sonar, ultrasound, and video components and circuits. Some tests that can be performed with standard function waveforms include frequency response characterization, device linearity characterization, digital logic generation, and DC-offset signal generation. The frequency response of a device under test (DUT) can be characterized by applying a swept sine wave to the DUT input, and measuring the relative amplitude and phase at the DUT output. Similarly, frequency response, distortion and linearity characteristics of a DUT can be observed by examining the time-domain response to a pulse wave signal input [1]. Figure 1 shows various output pulse distortions that can be caused by the non-linear amplitude or phase response of the DUT.

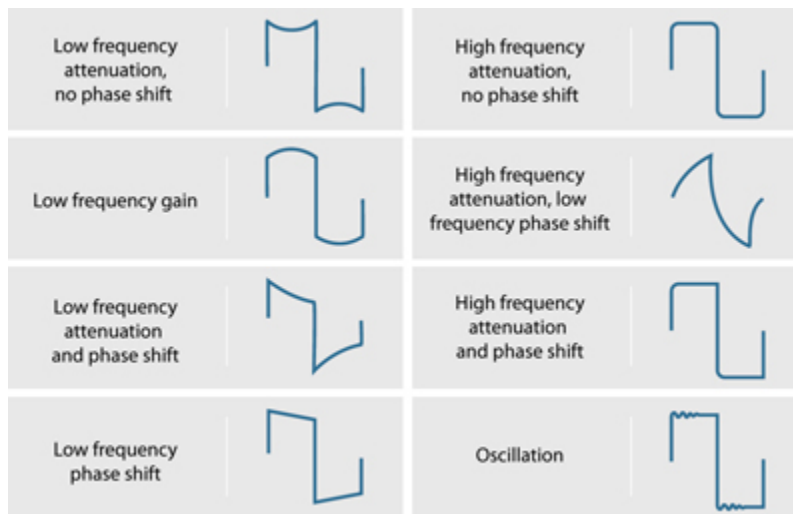


Figure 1. Pulse waveform responses

## Advanced Functions

Most AWGs provide other advanced functions such as multi-tone, AM, FM, cardiac, haversine, sinc pulse, Gaussian pulse, Lorentz pulse, noise and others [2]. These advanced functions typically address specific applications in specific industries. For example, haversine (sine waveform with DC offset such that the negative peak is at 0V) and cardiac signals are typical waveforms used in medical device testing. Different pulse shapes show another example of application-specific waveforms. Standard pulse waveforms excite the DUT with a broad harmonic content due to the sharp transitions in the signal. Other types of pulse waveforms have smoother transitions that

shape the harmonic content for specific applications (see figure 2). The sinc pulse is a shaped pulse with a bandwidth-limited frequency spectrum. Sinc pulses are used to characterize or excite communications channels with limited bandwidths. Lorentz and Gaussian pulses are used to simulate the signals from magnetic disk drives. The Gaussian pulse is also used to simulate dispersion or spreading in fiber optic cable transmission. Exponential pulses are useful to simulate physical phenomenon such as a resistor-capacitor charging circuit.

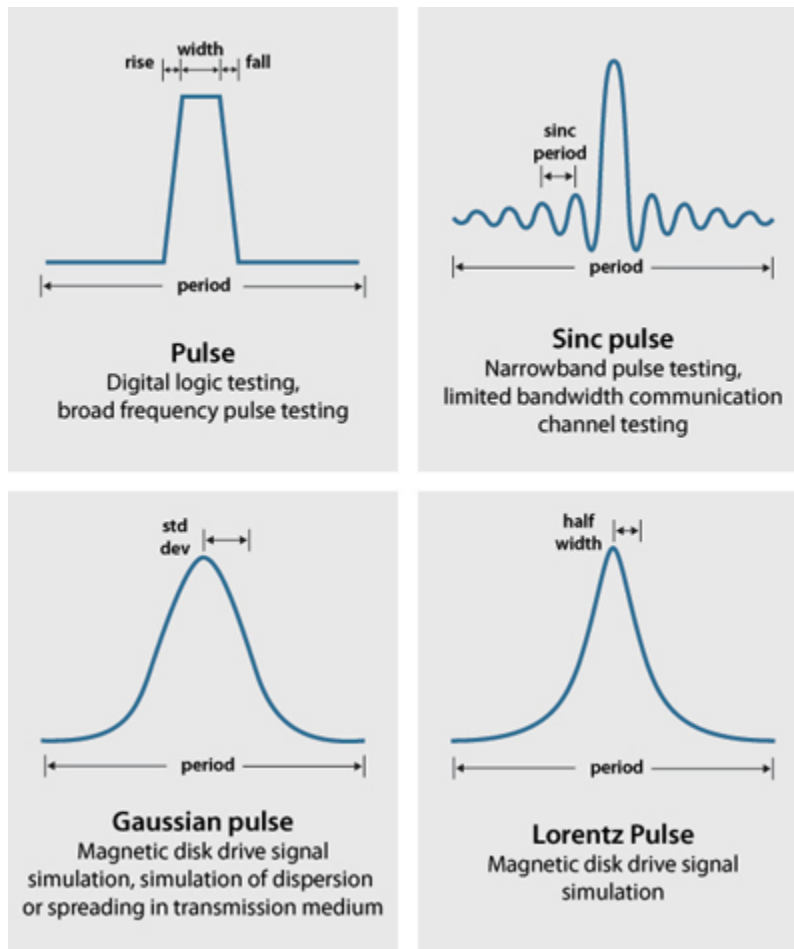


Figure 2. Various shaped pulse waveforms

Other advanced waveforms are useful for the design verification and production testing of electronic circuits and components. AM and FM signals are used within AM/FM radio testing. Multi-tone signals are used for intermodulation distortion (IMD) testing for amplifiers and other communication components. Broadband random noise is used for injecting noise into a system for measurements such as noise figure.

### Arbitrary Waveforms

Arbitrary waveforms involve the point-by-point user-defined waveform synthesis. This provides unlimited flexibility to the user to create custom waveforms not available on the instrument. The user loads waveform data codes to instrument memory, and programs the waveform size and

DAC clock rate. The DAC clock rate sets the time interval at which each data point is converted from digital data to an analog signal, and the waveform size controls the total duration of the user-defined arbitrary waveform.

Arbitrary waveform generators appear in a number of ATE test situations such as the generation of compliance waveforms, the synthesis of compound signal combinations, or the playback of signals captured with a digital oscilloscope. Examples of arbitrary waveforms that can be created mathematically and uploaded to the AWG include a video color bar pattern, an encoded serial communication test signal, a noisy sinusoid, or a digital pulse stream with runt pulses. Real-world signals such as a custom video frame can be captured with an oscilloscope and played back with the AWG. Another common AWG application is in combination with an RF/microwave signal generator. Sophisticated modulation is created and generated by the AWG and applied to a modulation input port on the high-frequency signal generator to create a modulated RF/microwave output.

### Waveform Sequences

Waveform sequences provide a mechanism to piece together standard or arbitrary waveforms in stages to create user-defined compound waveforms. Typically, a waveform library contains waveform data that are used in the stages of the waveform sequence. Waveform data in the library are reused and looped in a sequence to provide the flexibility to create long waveform sequences. Figure 3 illustrates a simple waveform sequence.

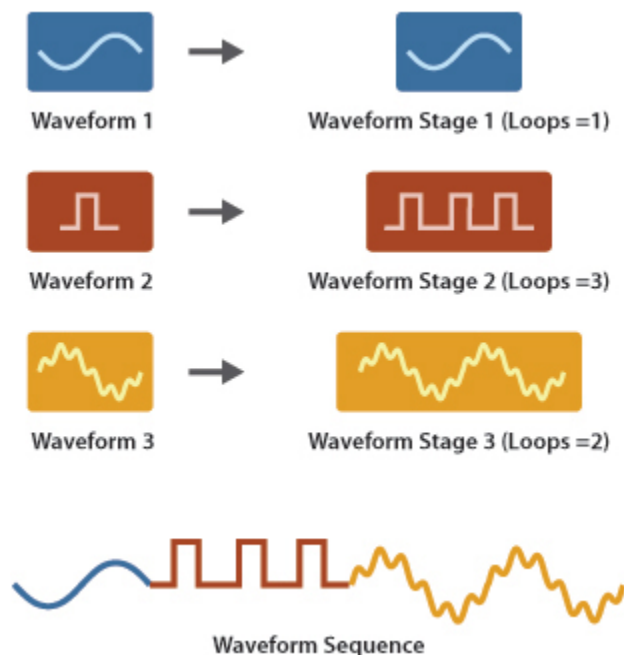


Figure 3. Example of an arbitrary waveform sequence

## Selecting An Arbitrary Waveform Generator

As electronics become increasingly complex, more sophisticated signal stimuli are required. Modern waveform generators are extremely powerful, but can also add significant complexity for the user. The arbitrary waveform generator, an instrument found in most test systems, is a very powerful signal synthesis tool. Unfortunately, many users take advantage of only a small fraction of the powerful features available to them in an AWG.

Selecting the right AWG can be daunting when comparing specifications such as DAC resolution, clock rates and topology, memory depth, sequencing, sweeping, triggering and synchronization. This section describes some of the common features found in an AWG, presents the technical differences between various signal generation techniques, discusses dynamic range limitations due to noise, accuracy and resolution, and presents the signal fidelity impact of clock topology.

## **Powerful Arbitrary Waveform Generator Features**

In addition to the ability to generate standard functions, arbitrary waveforms, and waveform sequences, an AWG offers other features to simplify the generation of a test signal. This section describes the common AWG features of triggering, sweeping, binary modulation, simultaneous load and play, and synchronization outputs.

Triggering or burst operating mode provides a method to synchronize one or more outputs to an external event. In burst mode, the instrument generates a discrete number of waveform cycles upon a trigger event. The number of cycles to generate is typically programmable. For standard functions and arbitrary waveforms, a cycle is one period of the waveform. For arbitrary sequences, a cycle is one complete progression through all the waveforms in the sequence.

The sweep operating mode provides a method to generate a swept-frequency output signal. When using sweep mode, the waveform shape in DAC memory is constant, and the DAC clock frequency is swept a linear or logarithmic fashion. Typically, the start and stop frequencies are programmable, along with the sweep time duration from start to stop. Sweep directions of up, down, or up and down are also typically selectable.

Binary modulation mode allows an external or internal modulation source to be applied to switch between two preloaded waveforms. This functionality enables amplitude shift keying, frequency shift keying, phase shift keying, toggling between two arbitrary waveforms, or gated signal generation. For each of these applications, waveforms for both states are preloaded and the output waveform is determined by the state of the modulation source. The modulation source typically is selectable between the external and internal sources. For example, an internal clock source can be used to toggle between the two waveforms at a user-defined rate.

Some arbitrary waveform generators offer a simultaneous load and play feature that enables the switching between output waveforms in a seamless fashion. A simultaneous load and play AWG provides upload access of the next waveform while the instrument is generating its present output waveform. In this type of AWG architecture, each waveform DAC has dual memory buffers. While one buffer feeds a data stream to the DAC for conversion to the analog output, the

other buffer can be loaded with the next waveform to be generated. This dual ping-pong buffer architecture enables instantaneous, seamless waveform switching upon command, trigger event or modulation input state.

Many AWGs provide synchronization pulses (SYNC) that can be routed to front panel or backplane outputs. SYNC outputs typically enable programmable binary outputs that toggle at user-defined time positions in the waveform cycle. SYNC outputs are useful for generating time marker or trigger output pulses that have an exact relative position to the output analog waveform(s).

## **System Requirements**

There are a number of requirements that play into the selection of an arbitrary waveform generator. Although requirements vary for different applications, most share the following general requirements for a waveform generator:

- Functionality requirements
- Number of waveform output channels
- Power levels of output signals
- Acceptable signal fidelity specifications
- Expected test throughput
- Budget constraints

Most of the above system requirements and tradeoffs can be easily quantified. Signal fidelity specifications may be less easily determined, and include such requirements as gain and offset accuracy, passband flatness, and spectral purity.

## **Spectral Purity**

The spectral purity (noise, spurious and harmonic distortion) of a test signal source should exceed that of the DUT. Spectral purity is especially important where the AWG is used as a modulation source for the RF/microwave signal generator. In commercial telecommunication markets, this includes applications such as testing of semiconductor devices used in wireless communications and infrastructure equipment. Military applications include testing of tactical radios, radar receivers, and electronic warfare systems.

For an AWG, spectral purity is sometimes quantified as its dynamic range. Dynamic range, typically expressed in decibels (dB), is a measurement of the difference between the largest and smallest signals that can be generated simultaneously. The theoretical maximum dynamic range of an AWG is limited by quantization noise caused by the DAC's bit resolution. The theoretical maximum dynamic range of an ideal DAC of N bits can be computed with equation (1). For example, the maximum dynamic range of an ideal 14-bit DAC is 88.6 dB.

$$\text{Dynamic Range} = (N \times 6.02) + 1.76$$

Equation 1

The non-ideal DAC and electronic devices in an AWG further limit the dynamic range due to noise and distortion. Thermal noise and shot noise are present in all electronic devices, and digital feed-thru noise can be significant in mixed-signal electronic circuitry. Distortion is caused by nonlinearities in electronic devices that create new frequency components not in the original signal. Spurious Free Dynamic Range (SFDR), Signal-to-Noise and Distortion Ratio (SINAD), and Effective Number of Bits (ENOB) are specifications on the signal dynamic range at an explicit output frequency [3]. These specifications include all noise and distortion components from DC to the Nyquist bandwidth. SFDR is the measure of the amplitude difference between the fundamental signal and the largest harmonic or non-harmonic spur. In effect, SFDR defines the usable dynamic range before spurious noise interferes or distorts the generated signal. SINAD is the measure of the difference between the fundamental signal and the total integrated noise and distortion components. As the signal frequency increases, SINAD decreases due mainly to distortion components. SINAD and ENOB quantify the same specification in different formats, and are directly related by equation (2).

$$\text{ENOB} = (\text{SINAD} \times 1.76) / 6.02$$

Equation 2

Intermodulation distortion (IMD) is another type of non-linear signal distortion that is often specified for a waveform source. IMD is a measure of the intermodulation products created by two frequency tones generated simultaneously in a single waveform. It is measured as the total power of selected intermodulation products relative to the total power of the two fundamental signals. The fundamental signals are typically of equal amplitude and close in frequency ( $f_1$  and  $f_2$ ). The Nth-order intermodulation products will occur at the frequencies shown in equation (3).

$$N \times f_1 - f_2, N \times f_2 - f_1, N \times f_1 + f_2, N \times f_2 + f_1$$

Equation 3

## Spur Reduction

Due to the digital nature of the AWG, its dynamic performance can be improved through the digital manipulation of the waveform data stream. The most significant spurious signals produced by an AWG are typically harmonics of the desired output frequency or aliased images in the DAC output spectrum. Spurious signals in an AWG can be reduced by combining the original signal with a replica of each spur that is phase-shifted by 180 degrees. The AWG output spectrum can be mathematically optimized by digitally adding a sinusoid in the waveform data with the proper magnitude and phase-shift to produce destructive interference and eliminate the offending spur.

## AWG Architecture Topologies

## AWG DAC Topologies

An AWG will specify a maximum DAC clock rate ( $f_c$ ) and an output signal frequency ( $f_s$ ). The maximum output frequency is limited by the discrete-time nature of the DAC. Sampling theory dictates that all frequency components in a generated signal must be within the Nyquist bandwidth of the DAC (one-half the DAC clock frequency or  $f_c/2$ ). The output of a DAC is essentially a series of rectangular pulses whose width is equal to the DAC clock period. A reconstruction filter is used on the DAC output to smooth this sequence of rectangular pulses. In mathematical terms, the reconstruction filter removes the DAC clock harmonics and removes the Nyquist image folded over at a frequency of  $f_c/2 - f_s$ . Note that the output signal amplitude is also affected by a  $\sin(x)/x$  roll-off due to the discrete-time nature of the DAC. Figure 4 illustrates the frequency-domain components of a DAC output including the Nyquist image. As  $f_s$  approaches  $f_c/2$ , the difference between the desired frequency  $f_s$  and the undesired frequency component at  $f_c/2 - f_s$  decreases. The proximity of the desired and undesired signal components places difficult constraints on the transition between passband and stopband of the reconstruction filter.

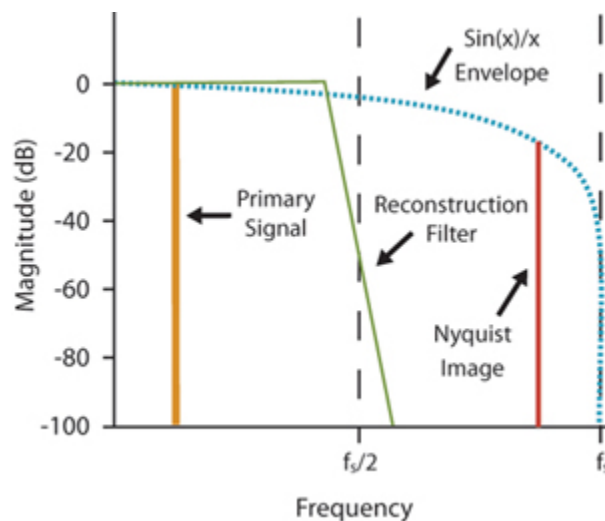


Figure 4. DAC output spectrum showing the Nyquist image

There are DAC topologies that extend the usable Nyquist bandwidth by increasing the DAC output clock rate above the DAC input data rate. In these cases, the waveform data is created at one clock rate and the DAC output is clocked at a second higher clock rate. This pushes the Nyquist image higher in frequency, simplifying the filter design and improving the dynamic performance. Two of these dual-clock topologies include interpolation and data re-sampling. The interpolation technique uses an interpolating DAC to reconstruct additional points between the input waveform data points. The reconstructed waveform is smoothed in a digital filter. Typically, a lowpass infinite impulse response (IIR) filter is used. Some interpolating DACs provide highpass filters to generate an image frequency above Nyquist. For an interpolating DAC, the output DAC clock frequency is an integer multiple (typically 2X, 4X, 8X, etc.) of the input data rate. Data re-sampling is another technique that improves the dynamic performance by increasing the DAC clock frequency. The data re-sampling technique uses a fixed high-frequency DAC output clock



frequency that is independent of the waveform input data rate. Digital processing is applied to the waveform data to digitally recreate a data stream at the DAC output rate. The input and output clock frequencies need not be harmonically related, and the original waveform data points may not appear in the output data stream. Instead, an unrelated time step is used to digitally reconstruct new DAC output points by re-sampling and filtering the original waveform data points. Because the DAC output clock is fixed, the data re-sampling technique uses a single reconstruction filter that is independent of the waveform data rate.

## Clocking Topologies

The DAC clock topology affects the spectral purity of the AWG. Two commonly-employed clock topologies include the direct digital synthesizer (DDS) and the phase-locked loop (PLL). A DDS is an open loop topology that has nearly instantaneous settling time. A PLL is a closed loop topology in which the stability of the feedback loop can be tuned to optimize dynamic performance. In the PLL, the frequency switching time is dependent on the settling time of the closed loop system.

A DDS integrates a programmable phase increment register, a phase accumulator, a sine look-up table and a DAC on a single device to generate the sinusoidal output clock signal (see figure 5). The DDS is an all-digital synthesizer that enables very precise and very rapid phase and frequency control. This equates to fine output frequency resolution and fast output frequency switching times. On the downside, the digital nature of the DDS creates non-harmonic spurious signals that degrade dynamic performance.

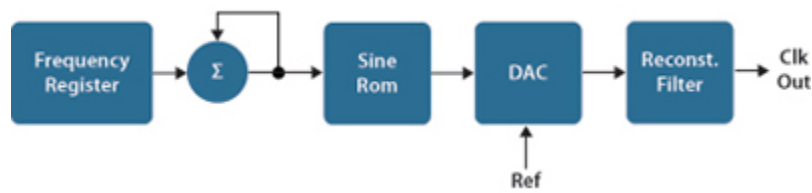


Figure 5. Direct digital synthesizer topology

A PLL uses programmable dividers, a phase/frequency comparator, a loop filter and a voltage controlled oscillator to generate the sinusoidal output clock signal (see figure 6). The PLL uses a feedback loop to track the reference and has a relatively slow loop settling time. There are two classes of PLL dividers: integer-N and fractional-N. Fractional-N PLLs enable finer frequency resolution, but do so by creating pseudo-random divide ratios that degrade spurious signal performance. If fine frequency resolution is required, an integer-N PLL will provide very slow frequency switching times. The benefit of the PLL topology is that its analog nature results in very good phase noise and spurious signal performance.

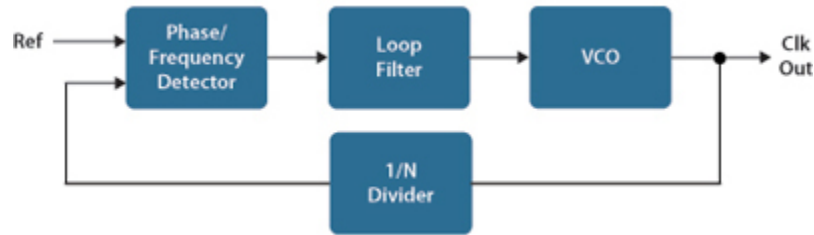


Figure 6. Phase-locked loop topology

Other clock topologies that combine DDS and PLL technologies include the DDS-driven PLL, the DDS-offset PLL, and the DDS-divided PLL. These three topologies take advantage of the benefits of each technology to simultaneously achieve the frequency agility and resolution of the DDS and the spur and phase noise performance of the PLL. See the references for more information on the topologies that combine the DDS and PLL [4].

## Conclusion

An AWG is a versatile instrument that can be used in a variety of test applications to generate signal stimuli. This paper provides a fundamental overview of some of the techniques, features and applications of an AWG. There is additional in-depth information for all of these topics for the interested reader. The overview information presented in this paper should help the user to select an AWG and find additional applications for an AWG in ATE systems.

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