Application Note

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Understanding Your Signal Generator Output Specification

This Application Note examines the building blocks used in the output stages of a typical signal generator and explains how they contribute and interact to affect the critical specification points of level accuracy and intermodulation performance.

Introduction

Before looking at the subtleties of specification parameters it is useful to examine the basic building blocks used in a typical signal generator.

Signal generators, whether they are stand-alone signal generators or part of a Mobile Radio Test Set, use complex systems to deliver a user selected amount of RF power at the required frequency, with or without modulation, and with as few spurious signals or other artifacts as possible.

They are tested and specified in as simple a way as possible to give the user a method of verifying the performance of the signal source. Real life applications however can involve more complex test scenarios of signal generators than the benign test conditions under which the specification is measured. This application note explains some of the common difficulties that are encountered in real life conditions.

Signal Generator Output System

The RF output system of a signal generator varies considerably according to the type of generator and the preferred architectures favored by different manufacturers. There is however a common underlying format. Figure 1 illustrates the concept of a basic variable output level system. The adjustable gain block satisfies the need for a continuously variable output. The stepped attenuator is required because the output level range of a practical variable gain block is insufficient to cover the operating level range needed from a professional signal source.

This very basic scheme is limited to CW and other signal formats with constant carrier amplitude modulation schemes such as FM. It also lacks the refinements of ALC, Automatic Level Control, for amplitude stabilization and RPP, Reverse Power Protection facilities. ALC also provides an opportunity to implement amplitude modulation schemes.

A more practical scheme employing ALC Output Levelling is shown in Figure 2. Here an RF drive signal is applied to the output amplifier via a limited range variable attenuator.

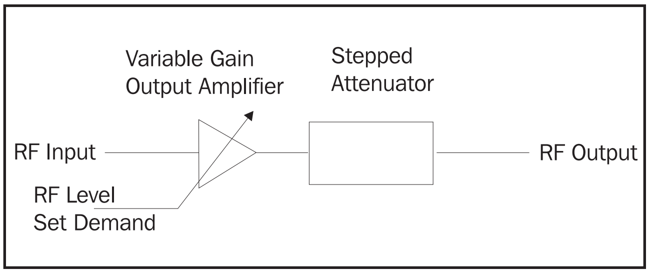

Figure 1 - Basic Variable Output Level System

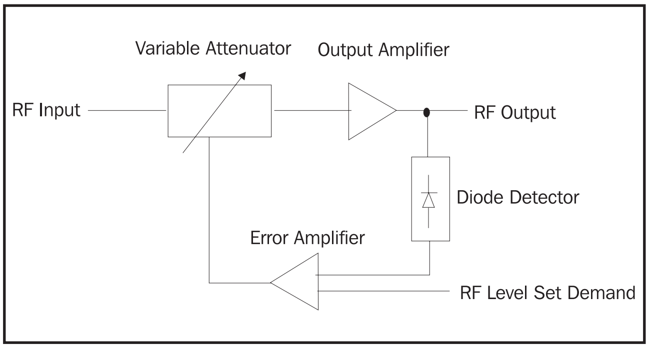

Figure 2 - ALC Output Levelling Loop

The output from the diode detector, which is proportional to the Output Amplifier RF output level, is compared with the RF Level Set demand in a feedback loop formed by the error amplifier and the variable attenuator. The servo action of the ALC loop ensures that gain variations in the RF drive voltage and the output amplifier do not appear in the RF output as level errors.

Figure 3 adds the remainder of the blocks to complete a practical output system with wide output level range, including a capability for AM, amplitude modulation.

Here the error amplifier input voltage is derived from a fixed level reference voltage. The reference voltage has any amplitude modulation required to be added to the signal generator output superimposed upon it. The resulting composite signal has its level adjusted (usually by a D-A converter).

The addition of AM to the reference voltage ensures that if the user requests AM, or other form of non-constant amplitude modulation, then the ALC system will not try to remove it.

Having obtained a precise RF level covering a limited output range the signal is then passed on to a switched multi-stage attenuator (which can use mechanical or electronic switches). The diode detector in the ALC has only a limited dynamic range, so this switched attenuator is used to increase the adjustment range of the RF output.

Once the signal has passed through the attenuator some generators then have an optional power amplifier which can be

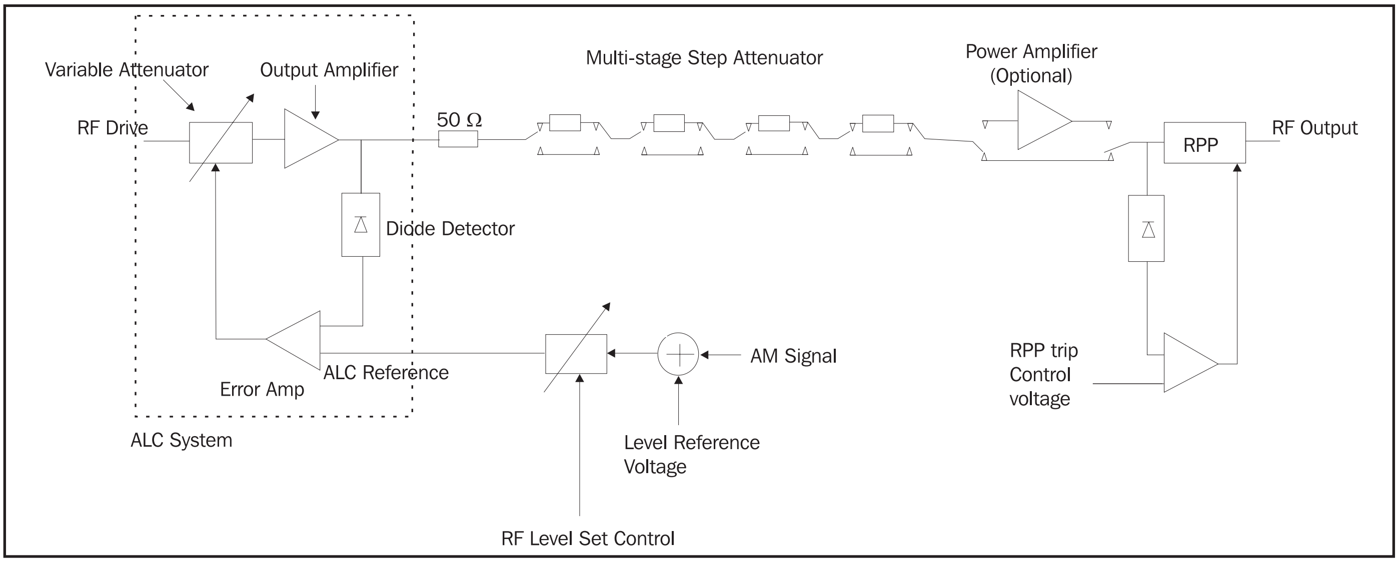

Figure 3 - Typical example of the Output System of a Signal Generator

switched in. This position is chosen for the amplifier since it does not have to overcome the loss of the switched attenuator, or avoid its non-linearity if it is an electronic attenuator. However, it cannot always be switched in since it also lifts the thermal floor noise of the signal from the switched attenuator when it is in circuit. Therefore at lower output levels it is switched out of use using a by-pass route. The objective has to be that when a low RF output is demanded the floor noise of the RF output is identical to that of a 50 Ω resistor (-174 dBm/Hz) so that measurements such as receiver sensitivity can be performed accurately.

Once the signal is past the power amplifier it then usually goes to a Reverse Power Protection system (RPP). The purpose of this device is to break the RF continuity at the output if the user accidentally applies either an excessive DC or RF signal to the output of the generator (e.g. he connects the generator to a keyed transmitter). If the continuity can be broken quickly enough it will prevent the applied signal from damaging the amplifiers or the attenuator of the signal generator - both of which can be expensive failures.

So the deceptively simple connector on the front panel of the signal generator is driven by a complex output processing system which can have an impact on how the generator behaves in normal use. Understanding the limitations and compromises with different types of output systems is an important factor in choosing a signal generator and its options.

Output Impedance

The output impedance of the signal generator is usually 50 Ω for RF applications and the output VSWR or the signal generator source specifies its accuracy.

Looking back into the RF Output Connector on the generator it seems obvious that the output impedance is 50 Ω, but is it - and under what conditions?

First, start with the output amplifier and ALC system in Figure 3. At the output amplifier there is an ALC system which ensures that no matter what the load impedance the output voltage will be the maintained constant at the point where the diode detector senses it. At this point looking back into the output amplifier it appears to have zero source impedance. Moving past the 50 Ω source resistor towards the output connector the impedance appears as 50 Ω - or does it? For the wanted RF signal as you vary the load the output impedance, as measured by, say, a sliding airline and a calibrated mismatch, it is indeed 50 Ω. However, if you were to connect a network analyzer at this point and measure it, the output impedance is 50 Ω plus the output impedance of the amplifier at the end of a transmission line. The 50 Ω output is a "virtual" source impedance for the wanted forward signal only, the actual output impedance seen by external loads looking back into the generator is something different.

Getting nearer the output connector the switched attenuator has a different output impedance as the switches change their states. When attenuation is added it masks the impedance of the output amplifier, and the first attenuator stages, depending on the order in which they are switched in.

Now we reach the switched power amplifier. When it is in use the external load sees the output impedance of the amplifier, often without the "benefit" of the ALC. When it is out of circuit the VSWR of the by-pass route for the power amplifier becomes visible.

Finally at the output connector the VSWR of the RPP comes into play. When the switch is closed the external load sees the circuits behind it (ALC, attenuator, power amplifier). When the switch goes open circuit all that can be seen is an open circuit at the end of a transmission line.

So the output impedance of a signal generator is a complex issue. It is highly variable with RF level, and dependent on the RF signal being generated and how the manufacturer configures the system by software. You can expect the VSWR to be reasonably constant over certain ranges but then the attenuator will be switched and the VSWR will behave in a very different way. That can have a significant impact on level accuracy in the test system.

Output VSWR Specification

Looking at the output VSWR specification of a signal generator it is commonly specified for signal levels below a specified value. The reason for this can be seen from Figure 3. Once an attenuator pad is switched in the effects of the output amplifier and ALC are masked by the loss of the attenuator pad. It then becomes relatively easy to specify the output VSWR - the attenuator, RPP and the power amplifier switching system (if fitted) dominate.

It is not necessarily the case that the output impedance is poor at higher output levels - it is just that its harder to measure on a production line as a routine test and the use of an ALC system complicates the definition of the term. In fact the manufacturer needs to keep good control of the output VSWR under these conditions since it has an impact on the RF output level accuracy. By omitting the specification at higher output power levels the need to do routine VSWR measurements in the acceptance or calibration test procedures described in the manuals is avoided.

RF Level Accuracy

The RF output level accuracy of a signal generator is considered to be a prime specification parameter. It can also be the most difficult parameter to measure over the full frequency and level range of a signal generator.

To provide accurate output signal levels the ALC system needs to compensate for the insertion loss between the output amplifier and the output connector. The first requirement is that the system is calibrated with all the attenuator pads switched out. If a switchable power amplifier is fitted an additional calibration is also required with it enabled to correct for the frequency response of the power amplifier and associated switching system. The correction factors adjust the output from the output amplifier as the frequency is varied. Clearly the flatter the uncorrected output can be made with frequency the fewer the correction points that need to be applied. A typical signal generator may need a calibration point every 150 MHz, with perhaps closer intervals as the frequency increases.

The reason for increased density of calibration data as the frequency rises is that there is more likely to be a worse VSWR and therefore more rapidly changing insertion loss. Calibration of the RF level can however be performed using the manufacturer's adjustment procedure and a power meter.

The problems become more complex as the RF level is reduced. When attenuator pads are switched in they are unlikely to be precisely their nominal value. As a result additional correction data is applied to correct for the pads. Each attenuator pad is designed to operate in a perfect 50 Ω system but the reality is different. As more attenuator pads are added their mismatches interact and cause errors that are dependent on which combination of pads is in use, and the distance between each of them. These are so called 'stacking' errors. It becomes harder to calibrate the attenuator. Therefore the worse the VSWR of the attenuator, the more complex the correction factors that need to be applied and the more complex the test procedure.

It also causes the user increasing problems when a signal generator has poor output VSWR but tight RF level accuracy specifications. Calibration of the generator requires increasingly complex test and correction routines to be performed with very demanding load accuracy conditions.

Take a simple example:

> If the output VSWR specification is 1.5
> The load VSWR is 1.1 (a very good match)
> Then the level uncertainty of a perfect power meter is ±1.8% or ±0.08 dB

To this has to be added the power meter uncertainty. If the overall signal generator specification is ±0.5 dB that means a great deal of uncertainty is taken up by the test equipment.

The situation gets worse if the source or load impedance VSWR is higher. For example with a source VSWR of 2 and a load VSWR of 1.1, the error with a perfect power meter becomes ±0.14 dB.

Source VSWR					***Load VSWR***						
	1	1.1	1.2	1.3	1.4	1.5	1.6	1.7	1.8	1.9	2
1	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1.1	0.00	0.02 -0.02	0.04 -0.04	0.05 -0.05	0.07 -0.07	0.08 -0.08	0.09 -0.10	0.11 -0.11	0.12 -0.12	0.13 -0.13	0.14 -0.14
1.2	0.00	0.04 -0.04	0.07 -0.07	0.10 -0.10	0.13 -0.13	0.16 -0.16	0.18 -0.18	0.20 -0.21	0.22 -0.23	0.24 -0.25	0.26 -0.27
1.3	0.00	0.05 -0.05	0.10 -0.10	0.15 -0.15	0.19 -0.19	0.22 -0.23	0.26 -0.27	0.29 -0.30	0.32 -0.33	0.34 -0.36	0.37 -0.39
1.4	0.00	0.07 -0.07	0.13 -0.13	0.19 -0.19	0.24 -0.24	0.28 -0.29	0.33 -0.34	0.37 -0.38	0.40 -0.42	0.44 -0.46	0.47 -0.50
1.5	0.00	0.08 -0.08	0.16 -0.16	0.22 -0.23	0.28 -0.29	0.34 -0.35	0.39 -0.41	0.44 -0.46	0.48 -0.51	0.52 -0.56	0.56 -0.60
1.6	0.00	0.09 -0.10	0.18 -0.18	0.26 -0.27	0.33 -0.34	0.39 -0.41	0.45 -0.48	0.50 -0.54	0.55 -0.59	0.60 -0.65	0.64 -0.70
1.7	0.00	0.11 -0.11	0.20 -0.21	0.29 -0.30	0.37 -0.38	0.44 -0.46	0.50 -0.54	0.57 -0.60	0.62 -0.67	0.67 -0.73	0.72 -0.79
1.8	0.00	0.12 -0.12	0.22 -0.23	0.32 -0.33	0.40 -0.42	0.48 -0.51	0.55 -0.59	0.62 -0.67	0.68 -0.74	0.74 -0.81	0.79 -0.87
1.9	0.00	0.13 -0.13	0.24 -0.25	0.34 -0.36	0.44 -0.46	0.52 -0.56	0.60 -0.65	0.67 -0.73	0.74 -0.81	0.80 -0.88	0.86 -0.95
2	0.00	0.14 -0.14	0.26 -0.27	0.37 -0.39	0.47 -0.50	0.56 -0.60	0.64 -0.70	0.72 -0.79	0.79 -0.87	0.86 -0.95	0.92 -1.02

Figure 4 - Mismatch errors (positive and negative) for combinations of source and load match. Excludes uncertainty in the power meter or other measuring devices

Figure 4 provides a table of the mismatch errors that occur for various source and load VSWR's.

The problem gets worse when the user tries to use the signal generator in a typical test scenario. If there is a cable between the signal generator and the device under test the load VSWR can be much higher and that will further degrade the accuracy of the test.

As the output power is reduced more correction data is applied to the output system to account for attenuator stacking errors, and the harder it becomes to verify the performance with even the best power meter. The better the output VSWR the less likely it is that errors are introduced. The easiest generators to test and use are those with a low output VSWR.

What is clear is that the issue of RF Level accuracy cannot be separated from the output VSWR specification of the generator. A poor output VSWR leads to increasing difficulty in verifying level accuracy and more complex calibration routines.

Attenuator Compromises

The attenuator design on a signal generator is a critical item since its performance largely determines the RF level accuracy, particularly when the RF level is low, and has a major impact on the output VSWR. The better the inherent VSWR of the attenuator the less likely it is to have interactive errors between the attenuator pads as they are switched in and out, and the simpler the adjustment and correction routines. It also leads to less additional errors and more predictable performance in typical use.

Attenuators are typically implemented using either electronic or mechanical switches.

Generally speaking mechanical attenuators are likely to have better VSWR (and therefore better uncorrected accuracy), not be prone to linearity errors and be more robust (in terms of accidentally applied reverse power). The mechanical switches can be either implemented using commercially available sealed switch assemblies or using an edge line switch structure. In general the sealed switches provide longer life while the edge line structures provide higher frequency cover, lower insertion loss and often better repeatability.

Electronic attenuators typically use either PIN diodes or FET's as electronic switches. The FET designs provide much better low frequency cover than PIN diodes, but their performance is rather less predictable (especially at low frequency) and they make fast acting fuses if they are not protected from external power sources. PIN diode designs can be extended to higher frequencies and lower loss than FET's, but require complicated drive arrangements because of the need for heavy forward current if non-linear behavior is to be avoided.

The insertion loss of electronic attenuators is generally higher than their mechanical equivalents and this makes it more likely that switched high power amplifiers are required if restrictions in output level are to be avoided (the linearity issues also make this more likely).

Electronic attenuators typically have a much longer life than mechanical attenuators, have good repeatability, but are more likely to suffer changes in performance with temperature.

The linearity of solid state attenuators and their loss can have a major effect on the design of the signal generator, especially when complex modulation schemes or combining systems are deployed.

The higher typical VSWR of electronic attenuators also means they are likely to have much more complex RF level calibration systems, requiring more calibration at more levels. This leads to the need for complex interactive algorithms to optimize the performance. Calibration over the full power range using specialist test fixtures is much more likely to be required than with mechanical attenuators.

RPP Systems

The RPP system is an important element in the design of the output system. Usually two lines of defences have to be used to protect against the application of reverse power.

The first is a relay (typically a coaxial reed relay since they are fast acting) which goes open circuit when power is removed from its drive coil. If reverse power is applied a detector at the output registers its presence and opens the switch. The switch is then required to break the RF signal that has appeared at the output connector. Breaking this signal can be a non-trivial event since as the switch goes open circuit it starts generating a very high VSWR. Arcing can then occur which may damage the relay contacts.

This is made worse by the fact that historically the most common source of reverse power has been a transmitter and a transmitter frequently has a very poor output VSWR for transmitter efficiency reasons. The arcing can be very destructive and for this reason IFR specifies their protection systems from a very adverse source VSWR. This more accurately reflects real life applications. IFR design testing of these circuits utilizes a cavity power oscillator with a very poor output VSWR (≥10:1). A sliding line is used to adjust the phase of the relevant signals for the worst arcing condition. In contrast to this approach some products are specified in rather more benign (and sometimes unrealistic) environments.

The RPP relay is usually arranged to be open circuit when the mains power is removed to maintain protection of the generator against reverse RF power when the generator is left connected into a test system.

The second defense mechanism is an electronic clamping system. The relay protection system takes time to operate and while the contacts are still closed the externally applied power continues to stress the RF components in the output system. This is particularly a problem with FET's which can fail very quickly compared to the operating time of the relay. A clamping arrangement should be incorporated which acts quickly to reflect the RF power from the external source and protect the output system.

When the two lines of defense are combined the net result is that a point in the output system produces a short circuit to reflect power back to the source and then a relay system breaks the signal and produces an open circuit at a different point in the system. This all happens at a distance from the external power source and can have an effect on it. If the external power source does not have its own protection system to allow it to be connected to a poorly controlled external load VSWR then this could cause a failure to occur. The RPP system is there to protect the signal generator, not the offending source of power.

AM and Transient Behavior

For an analog signal generator there are a variety of ways used to produce amplitude modulation. The simplest scheme is to use the ALC system to produce AM - usually known as envelope feedback. The wanted AM signal is added to the RF Level reference voltage, shown in Figure 3, and therefore appears on the ALC reference. The ALC system then forces the RF output to be modulated in sympathy with this varying voltage. The ALC is required to have a large bandwidth in order to ensure the modulation is relatively distortion free and the detector has to be designed to be linear (or the signal has to be pre-distorted to correct for the non-linearity). The IFR2030/40/50 series signal generators use envelope feedback and the result is excellent broadband AM performance - a feature that is exploited in the avionics variants of the instruments.

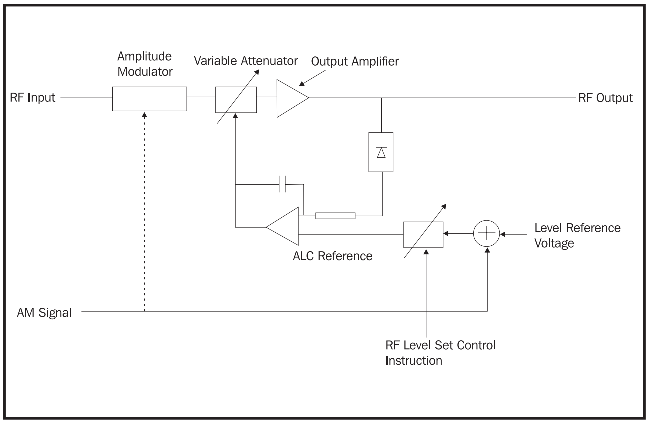

Figure 5 - Generating AM with separate modulator

AM can also be generated by the use of a separate AM modulator as in Figure 5. In this case the ALC system still needs a reference voltage that carries a representation of the AM signal, but the ALC BW does not have to be as large. (This can simplify the overall design of a broadband signal generator). For modulation signals outside the BW of the ALC system the AM is controlled by the AM modulator but inside the ALC bandwidth the ALC system controls the eventual AM depth. There is a crossover region where the two control systems must be arranged so as to not fight each other. There is also an inevitable compromise that the AM depth accuracy may change slightly above and below the ALC bandwidth. Such systems are not well suited for avionics ILS testing where AM flatness is critical to the application.

The bandwidth of the ALC leads to a potential problem in suppressing positive RF level transients when changing frequency or level. A positive level transient can prove to be destructive when the signal generator is testing high power amplifiers, or could cause erroneous failures when performing EMC tests. All IFR signal generators use software sequencing to suppress any significant positive transient.

The transients arise because of the interaction of the electronic (ALC) level control and the attenuator having different response times for a level change, or from a frequency change temporarily exposing a change in the gain of the output system with frequency. A filter change, an oscillator change, a divider change - or any other change of setting in the generator architecture could cause this. It could also be simply un-flatness in the system.

Figure 6 shows the sort of problems that can occur.

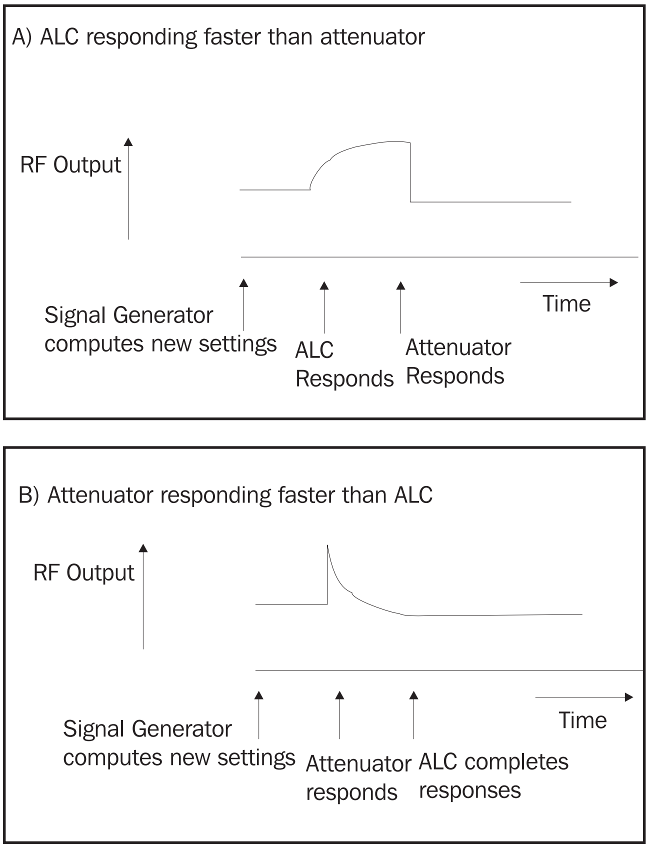

Figure 6 - Transient effects caused by the interaction of attenuator and ALC

If the ALC bandwidth is high it may change the output level faster than the attenuator. If the generator uses a 10 dB step attenuator and has a top range of 0 to +10 dBm, and if the level is changed from 0 dBm to -1 dBm, the ALC may increase the output by 9 dB before the attenuator switches a 10 dB pad into circuit.

If the ALC BW is slower than the attenuator, and taking the same signal generator ranges, and if the RF level is changed from -1 dBm to 0 dBm the output will rise to +9 dBm until the ALC reduces the level.

A worse situation can occur because of attenuator timing. If attenuator pads are removed before they are inserted very large transients can be generated. Take the above example with the generator providing a -21 dBm signal (a 20 dB pad in circuit). If the level is changed to -11 dBm (a 10 dB pad in circuit), and the 20 dB pad switches out before the 10 dB pad is switched in, a positive 10 dB transient is generated. At low levels the relative amplitudes could be much worse.

For this reason the manufacturer of the signal generator should include software routines to sequence the RF level changes to avoid these positive transients. This leads to unavoidable negative transients. If a major change of conditions is caused by a frequency change the RF output should be temporarily suppressed to avoid positive transients. This does slow the operation of the signal generator down, but it is preferable to causing damage to the devices under test.

Combining Signal Generators

Another common test scenario for signal generators is applications where several signal generators need to be connected together through a combiner. A brief examination of test procedures for radio and amplifier systems reveals a host of applications for such a configuration. The implications for the signal generator are much more complex than is commonly realized.

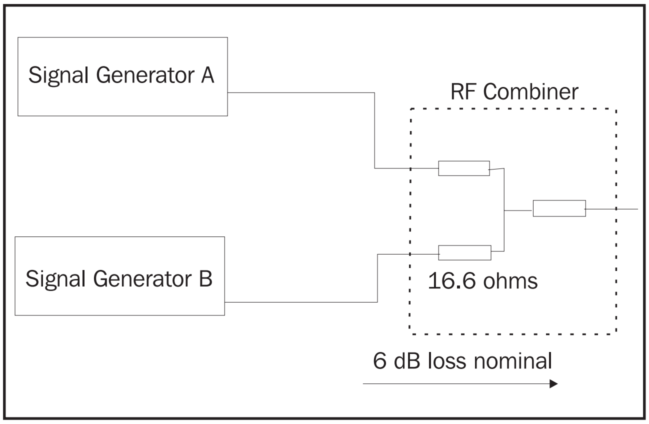

Figure 7 - Simple resistive combiner used for combining signal generators

Consider the combiner system connecting signal generators shown in Figure 7. Suppose each signal generator is set to generate a signal of +7 dBm into the resistive two-port combiner. The loss of the combiner is nominally 6 dB between each port when they are terminated in 50 Ω.

Signal generator A injects a signal of +7 dBm and +1 dB appears at the output port. However the same signal also appears at the port connected to signal generator B so it has a spurious signal on its output at +1 dBm. The same thing happens at signal generator A output, the signal being injected by signal generator B. This causes three major problems.

The first is intermodulation. The non-linearity in the output system of the generator generates intermodulation products because of the forward signal at +7 dBm and the backward signal at +1 dBm. If you are trying to measure the intermodulation of a device connected to the output of the combiner there is a good chance it will be masked by these intermodulation products. The non-linearity could be due to the RPP detector, the ALC detector diode, the electronic attenuator or the output amplifier - or more likely a combination of all of them. This is also not a commonly specified parameter on a signal generator, so don't look to the data sheet for help.

The second problem is that it can change the RF output level. The detector diode in the ALC detects both the intended forward signal and the reverse signal. The detector will typically respond by lowering the level of the output signal via the ALC system.

The third problem is a little more subtle. If the frequency separation of the two signals is not at least an order of magnitude greater than the ALC BW the detector will see the amplitude of the two carriers "beating" together and try to eliminate it by introducing AM on the forward signal. This is in fact impossible to do since the interfering signal has only one main frequency component, whereas AM introduces two symmetric side bands. In trying to suppress the beat signal the ALC introduces a more complex set of side bands through this AM process. As the frequency separation of the two generators is increased the impact is reduced; as they come closer together the effect is worse. The frequency offset at which this becomes apparent is dependent on the ALC system and the level of side-band free operation that is required.

The example above used a resistive combiner. Better results may be obtained from a commercially available reactive combiner. However, the performance then becomes less predictable. The improvement arises because the reactive combiner provides greater isolation between signal generators than the simple resistive arrangement. The degree of isolation is very dependent on the VSWR of the devices connected to it - the specification on isolation only applies with perfect 50 Ω sources and loads. Again, taking the example above, if the generators have no attenuator pads switched in the question of output VSWR specification arises. This poses an issue since manufacturers typically do not specify VSWR at high output levels. Worse still, going back to Figure 3, the output impedance for this purpose is not simply the 50 Ω defined by the virtual earth formed by the ALC system - it is the VSWR of the whole output system including the 50 Ω source resistor. Only when the first attenuator pad is inserted is the combiner likely to see a reasonably guaranteed 50 Ω impedance match.

Once attenuator pads start to be switched in the source match is improved but a poor output VSWR specification on the signal generator will still limit the combiner isolation, which in turn will limit the improvement in the intermodulation, level and result in AM problems as described above.

Commercially available reactive combiners also tend to limit the frequency band of operation of the test system compared to resistive combiners.

The IFR 2026A/B family of signal generators overcome many of the limitations described above. The reactive combiner system employed covers a frequency range much broader than commercially available devices together with carefully controlled RF hardware to maximize the isolation. The signal generator is conservatively specified in terms of intermodulation performance at a realistic 1.5:1 output load VSWR - if the user provides a better load match the performance naturally improves. As a consequence it provides a trouble free method of multi-carrier testing to 2.51 GHz.

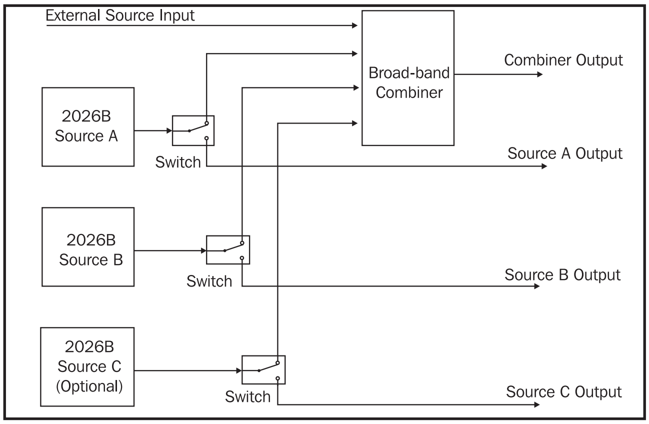

Figure 8 - Output system of 2026A/B series Multi-source Signal Generator

Summary

Understanding how your signal generator delivers and manages the RF signal that is provided at the output connector can be an important part in getting the best out of your product purchase - and help you to choose the signal generator that is best for your application. It is important to understand the relationship between the useful RF level accuracy and the output VSWR, and the consequential impact on cost of calibration when products offer good accuracy with poor output VSWR.

Applications for testing EMC or power amplifiers require signal generators that carefully control the sequencing of internal instrument settings to avoid positive level transients - a feature that is a part of every IFR signal generator.

For applications requiring multiple signal generators to perform a test there is a considerable advantage in using the integrated solution provided by the IFR 2026A/B family.

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Part No. 46891/904, Issue 2, 03/04