LINEAR AMPLIFIERS FOR DIRECT-DRIVE TESTING

Direct-drive testing is a precise and cost-effective method of assessing damage limits and upset tolerances of subsystem elements.

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INTRODUCTION

Direct-drive testing using linear amplifiers provides a precise and cost-effective tool in the development and verification of systems designed for service in severe electromagnetic environments. Traditional electromagnetic pulse (EMP) testing has utilized full illumination testing of the total system in a large simulator, but the limited availability and high cost of this option makes it inappropriate for many users. Large-scale testing of individual subsystems or line replaceable units (LRU) requires a more reasonably priced and versatile testing system.

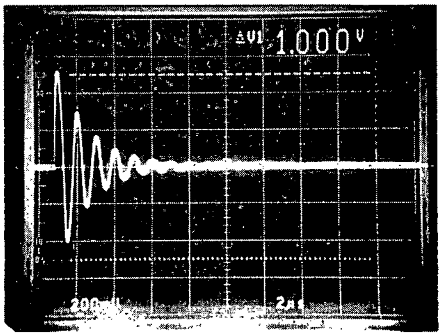
The needed alternative is attained by direct application of high-level electrical stimulus to the individual elements of a system at the various predicted points of entry to the LRU. This direct application is termed direct-drive testing. This alternative is made feasible by two basic facts. First, electrical stress experienced by the typical LRUs is generally much lower than that experienced by the host system because of the incidental and deliberate shielding of the unit; thus test levels required for the LRU are much lower than those needed for total-system testing. Second, the historical record of full-illumination testing has provided an excellent basis for predicting the stresses that LRUs might encounter in specific application environments. Although the determination of the actual drive stimulus to be applied is a somewhat theoretical and relatively controversial subject, such standards as MIL-STD-461,[1] and SAE-AE4L-81-2[2] are serving to bring some standardization to direct-drive testing for various application environments.

There are at least three major methods of direct-drive: surface injection, bulk injection, and pin injection. Surface-injection testing involves the injection of relatively high currents (perhaps in excess of several thousand amperes peak) through the skin or other external conductive surfaces of the unit under test. Bulk injection is used to drive the interconnecting cables within a system with a "bulk" current, several tens of amperes to perhaps several hundred amperes. Direct pin-injection is used to apply relatively low drive levels (with respect to typical EMP testing), typically below 2000 V and 20 A peak, directly into the individual interface pins of an LRU or other subsystem element. The use of direct drive test procedures provides a precise and cost-effective method of assessing both damage limits and upset tolerances of subsystem elements. There are, however, relatively few commercially available systems providing the versatility needed for cost-effective large-scale testing.

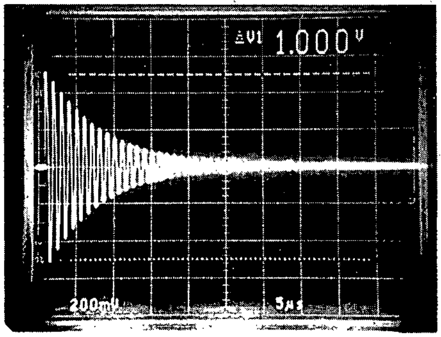
PULSED-POWER SOURCE

The critical element of a versatile, cost-effective direct-drive test system is the pulsed-power source. There are generally two competing source technologies for this application: energy dump configurations and linear amplifiers. The energy dump devices, also termed charge-and-dump or ballistic pulsers, store the required energy for a test pulse in a capacitor or inductor. The linear RF power amplifier offers versatile capabilities as the basis for a pulsed-power source. This versatility, however, is provided at the expense of maximum available drive level, but the typical requirements of direct-drive testing can be accommodated with linear amplifier based units.

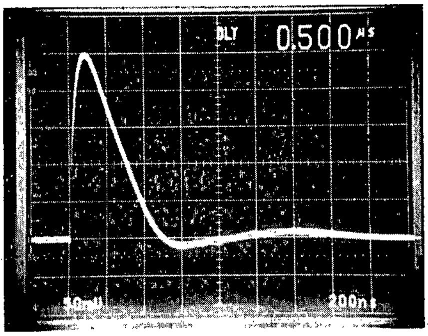
One criticism often directed against linear amplifier systems is the comparatively higher cost as compared to energy-storage systems. For individual instruments that may be true; however, if an energy-storage based system and a linear amplifier based system of the same capability in waveform and parameter selection are compared, the costs are similar. Also, the linear amplifier system supports programmable control over the entire performance range of its parameters while the energy-storage units typically require manual module changes to support the total range of requirements in typical direct-drive tests. This feature makes the linear amplifier-based systems ideal candidates for automated high-



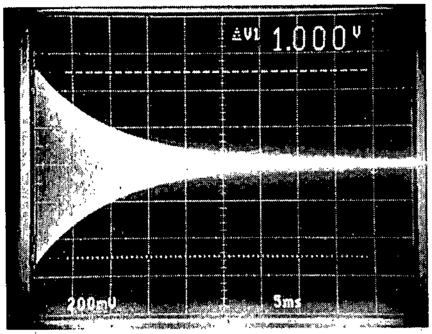
a. Q = 6



b. Q = 24

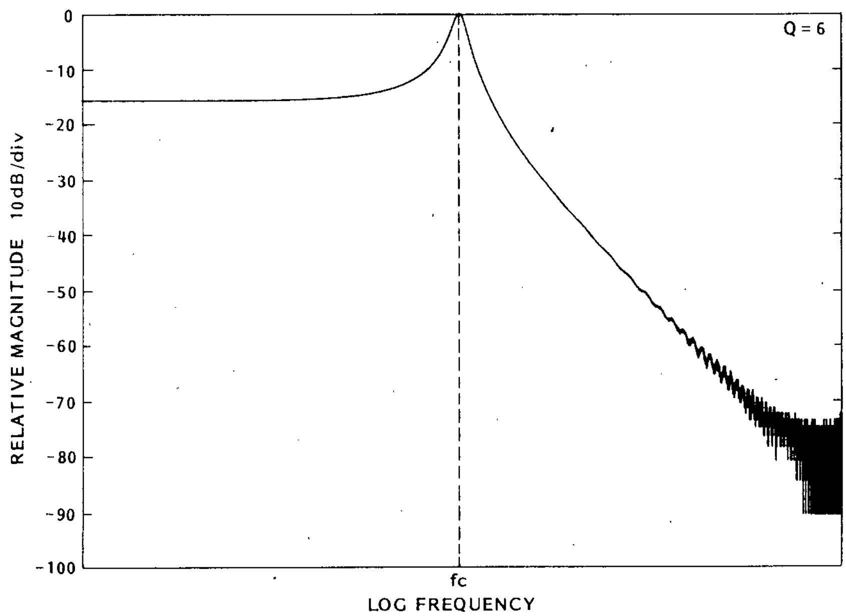


c. Q = 0.5



d. Q = 50,000

Figure 1. Commercial Damped-Sine Generator Output For Several Q Values at 1 MHz.



2A. Q = 6

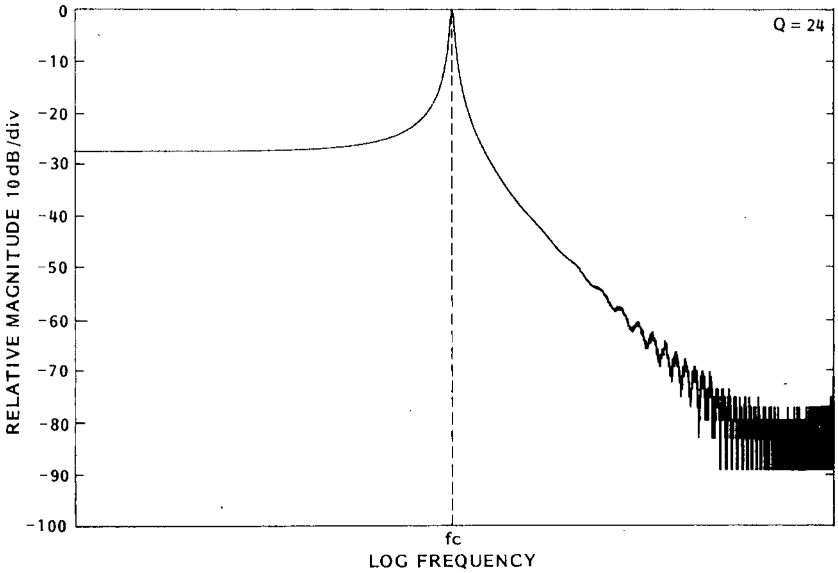
Figure 2. Analytic Ideal Damped-Sine Spectra.

volume testing.

The linear amplifier provides a linear transfer function allowing the application of any arbitrary test waveform within the bandwidth and level capabilities of the unit. Typical waveforms specified for direct-drive testing are: damped sinusoid, burst sine, continuous wave (CW) double exponential, square pulse, and doublet. The damped sinusoid is the most common. The linear amplifier allows the generation of complicated waveforms at a low level followed by amplification to the desired test levels by the linear transfer function of the amplifier. Since complex waveforms are quite easily generated at low levels by use of custom circuitry and such commercial instruments as damped-sine and arbitrary waveform generators, the linear amplifier makes available almost any desired test waveform with programmable control of the individual waveform parameters. Commercially available damped-sine generators are available that cover the full testing frequency range, but unfortunately, presently available commercial arbitrary waveform generators do not meet the total needs of frequency and resolution over the typical direct-drive test spectrum. If waveforms other than damped sines are required, a combination of signal generators may be required.

AMPLIFIER FREQUENCY RESPONSE REQUIREMENTS

The commonly used damped sinusoid is the waveform used as an example throughout this article. The range of characteristic frequencies for damped sinusoid applications is typically 10 kHz to 100 MHz. The Q values range from perhaps 1.0 (essentially a double exponential) to more than 10,000. Two common Q values of 6 and 24 at 1 MHz are shown in Figures 1A and 1B as output from a commercial damped-sine generator. Figures 1C and 1D show



2B. Q = 24

Figure 2. Analytic Ideal Damped-Sine Spectra.

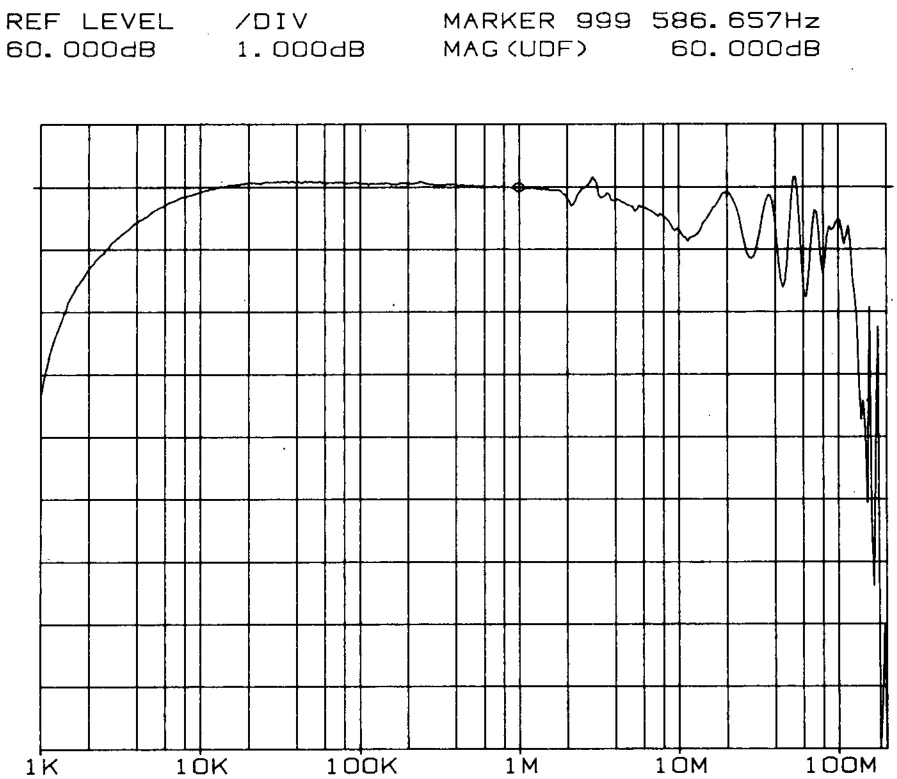
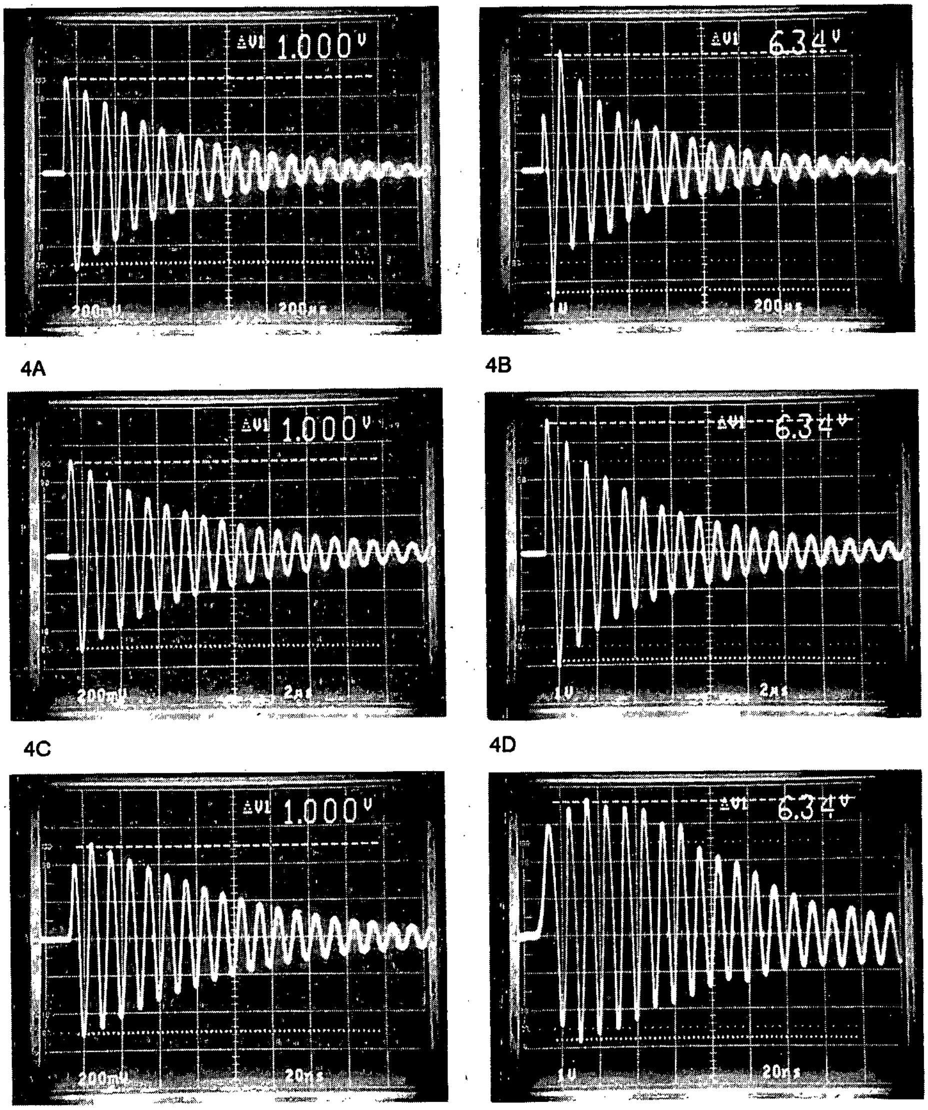


Figure 3. Frequency Response of a Typical RF Power Amplifier Used for Direct-Drive Applications.

the output waveforms at the performance limits of the damped-sine generator as an example of the wide variations in waveforms that a linear amplifier must handle from even this one instrument. To reproduce a damped-sine waveform the linear amplifier bandwidth must be sufficient to reproduce the critical spectral components of the waveform. The analytic spectra for ideal waveforms of those of Figures 1A and 1B are shown in Figures 2A and 2B respectively. The low-frequency components extend to dc as would be expected. The spectrum peaks at the characteristic frequency, f_c, and then drops at a slope asymptotic to 40 dB/decade. A practical linear RF power amplifier cannot pass the entire damped-sine spectrum, but such practical units can reproduce a "good" damped-sine waveform.

The characteristics of a good damped-sine waveform are presented below. The ultimate challenge in waveform purity specification is to have those demanding testing and those having testing demanded of them agree on real waveforms that can be practically generated.

A linear amplifier system must have a lower -3 dB frequency response about a decade below the lowest characteristic frequency of interest in order to reproduce sufficiently the spectral content of the damped-sine waveform. The rapid decay of spectral content above the characteristic frequency requires an upper -3 dB frequency response about an octave above the highest characteristic frequency of interest for reasonable waveform fidelity. Thus a suitable linear amplifier must have a bandpass of about 1 kHz to 200 MHz. To demonstrate the effect of the amplifier bandpass limit, three pairs of waveforms are shown in Figure 3 taken at the lower frequency limit, midband, and upper test-frequency limits. Both the input and output waveforms are shown for comparison. These data were col-



4A 4B 4C 4D 4E 4F

Figure 4. Effect of Amplifier Bandpass Limiting on Damped-Sine Output. (Scale = 100 V/V, Load = 50 Ohms)

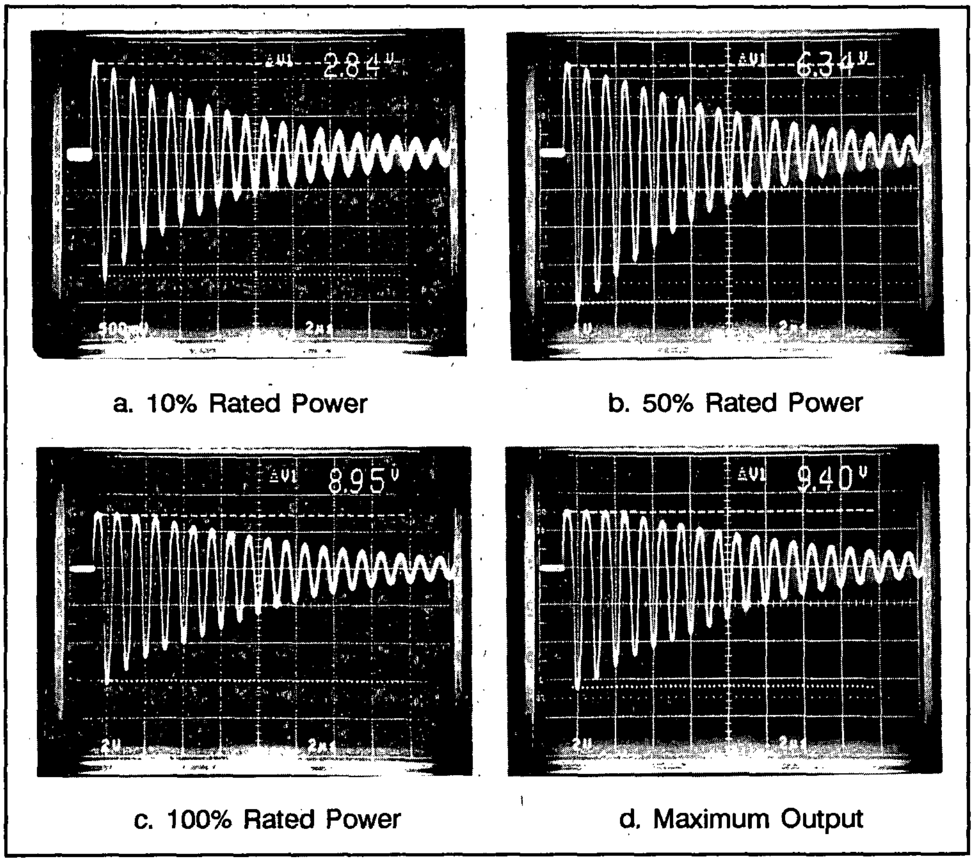
lected using a commercial damped sine generator and an RF-power amplifier with a -3 dB bandwidth of about 1 kHz to 200 MHz and capable of delivering approximately 2 kW CW, 20 kW peak into 50 ohms. The amplifier bandpass is shown in Figure 3. The measurements were made at a low level (1 kW peak) to minimize distortion. Figures 4C and 4D show that at the midband region of the amplifier response, 1 MHz, the waveform retains good fidelity. At a characteristic frequency of 10 kHz, Figures 4A and 4B show that the low frequency cutoff of the amplifier at 1 kHz results in the first cycle being about 20 percent low in peak amplitude. This waveform differs noticeably from an ideal damped sinewave.

At a characteristic frequency of 100 MHz the waveshape is somewhat similar to that at 10 kHz, as shown in Figure 4F. Also, the damped sine generator itself is just at its limit of performance at 100 MHz, as is evidenced by the low amplitude of the first peak in Figure 4E. The output waveform of Figure 4F is obviously less than an ideal damped sinusoid. For this particular system, the first peak equals that of the second at about 70 MHz and below 50 MHz, the waveform appears to be a subjectively good damped sinusoid.

DISTORTION

Another important linear amplifier parameter is the distortion of the waveform that occurs as a function of output level. The output power capability of a linear RF power amplifier is generally specified in terms of a CW average power into some specific load (not necessarily a matched load). Some correlation between the CW specification for an amplifier and its output capability for damped-sine transients is required. A true average power specification for the damped sine is of little value since the average power involved in a typical repetitive damped-sine signal is quite low compared to the amplifier capability required to supply it. Also, it is repetition-rate dependent. The power of a single pulse averaged over a very long time compared to its pulse width will approach zero. One simple specification is the instantaneous peak power, or simply the peak power, at the largest peak of the specific signal. The peak power is simply the magnitude of the peak potential squared, divided by the load resistance. In the case of a voltage/current specification, the peak power is the product of the magnitude of the peak potential and peak current. For a CW sinusoidal signal, the peak power is then a factor of two above the average power.

Perhaps the best specification for relating damped-sine parameters to the power capability of an amplifier is Equivalent Average Power. The Equivalent Average Power of the damped-sine signal is simply the average power that would be delivered to a load by a CW signal with a peak-to-peak magnitude equal to the peak-to-peak value of the largest cycle of the damped-sine signal. In



a. 10% Rated Power   b. 50% Rated Power

c. 100% Rated Power   d. Maximum Output

Figure 5. Effect of Amplifier Distortion on the Damped-Sine Waveform. (Scale = 100 V/V, Load = 50 Ohms)

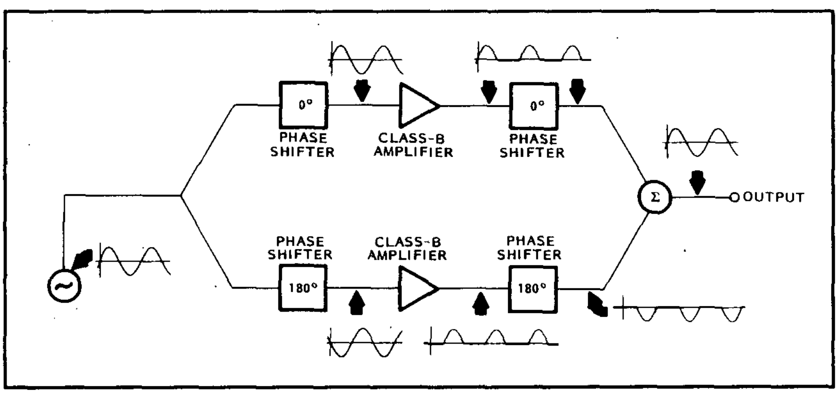


Figure 6. Simplified Push-Pull Configuration Block Diagram.

general, if an amplifier is capable of delivering a certain CW peak-to-peak level to some load, it can deliver the same peak-to-peak level (into the same load) of a bipolar transient such as one cycle of a sinusoid. However, it should be noted that many RF power amplifiers utilize a dynamic bias and other features that affect the transient response since they are generally intended for service with modulated CW signals. There, transient performance is of little concern.

Any amplifier will distort a signal if the level is raised high enough. Different amplifier classes and configurations of generally similar amplifier elements exhibit different degrees of distortion, and the optimum configuration is a function of the application and the amount of distortion that can be tolerated. Figure 5 shows the output of a 2 kW linear amplifier (two 1 kW linear amplifiers configured in parallel) at equivalent average power levels of 10 percent, 50 percent and 100 percent of rated power (rated CW average power) and maximum output power. The input signal for these output waveforms is the same as that of Figure 1B. At 10 percent of rated power, the input waveform is quite faithfully reproduced. At 50 percent of rated power, a noticeable compressing of the positive peaks is present. At 100 percent of rated power, the positive-peak compression is very noticeable. The distortion seen at maximum output is markedly dissimilar from that at full rated power, but that should be expected. If the amplifier could deliver higher power with less distortion, it would have a higher power rating. The amplifiers used in this example are Class A distributed transmission line amplifiers, and the distortion seen is classic of Class A amplifiers.

The distortion may be reduced by operating the amplifiers in push-pull. In a push-pull configuration, both amplifiers drive the load in-phase, but the amplifier outputs operate 180 degrees out-of-phase. This is accomplished by inverting one of the amplifier outputs before combining and inverting one of the input signals to compensate for the output inversion. Technically, which input and output signals are inverted does not matter. Figure 6 shows a simplified block diagram of a pair of Class B amplifiers in a parallel push-pull configuration.

To demonstrate the distortion performance of the push-pull configuration, the pair of 1 kW amplifiers used to produce the data of Figure 5 were configured in parallel push-pull, and the same data were collected and are shown in Figure 7. The amplifiers could be combined just as effectively in series push-pull

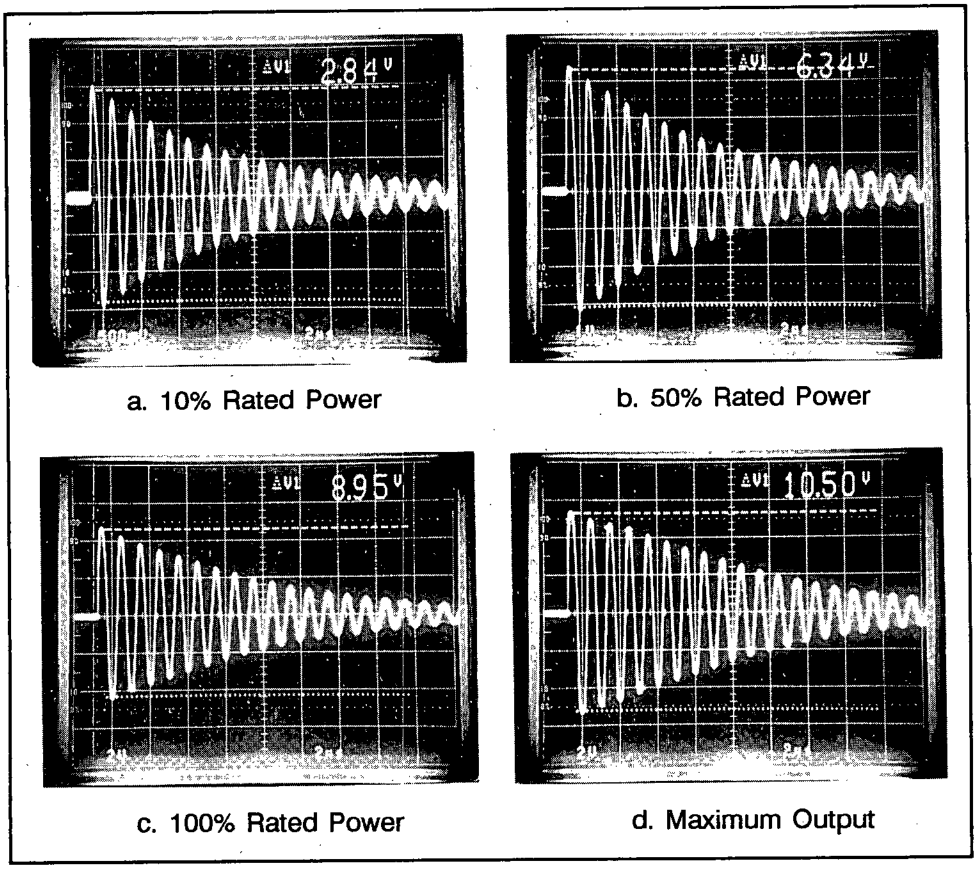


Figure 7. Amplitude Performance of a Parallel Push-Pull Configuration. (Scale = 100 V/V, Load = 50 Ohms)

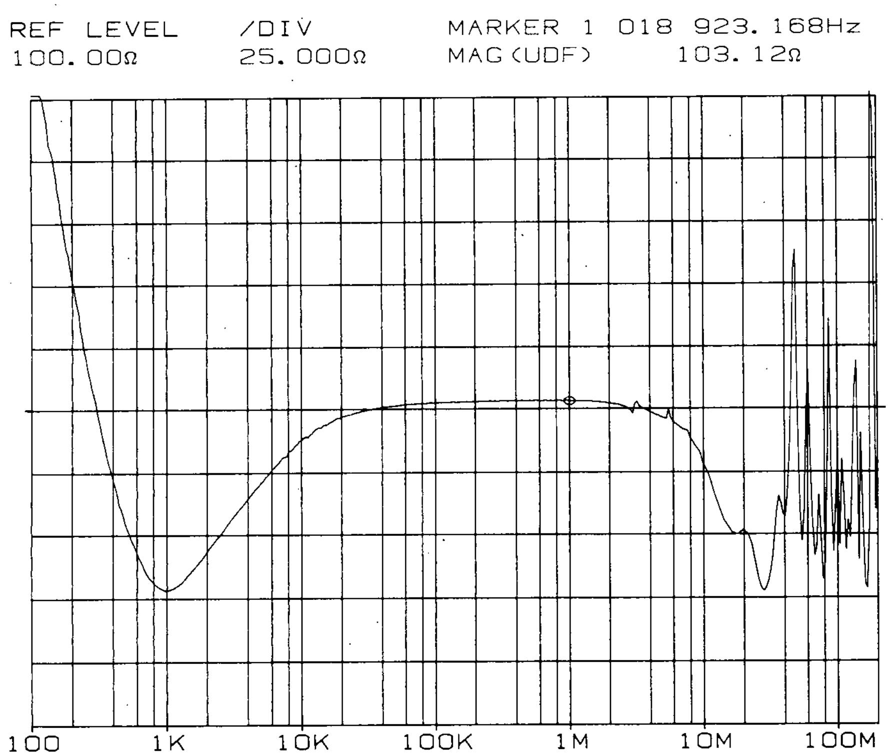


Figure 8. Typical 1 kW Linear RF Power Amplifier Output Impedance as a Function of Frequency.

to present a higher source impedance, but the available power and distortion would be similar to the parallel case. At 10 percent and 50 percent of rated power the output signal is very accurately reproduced with essentially no compression of either positive or negative peaks as was seen in Figure 5. Even at rated power, the wave shape is quite good with only subtle distortion in the decay envelope. At maximum available output, the waveform distortion is more obvious but much more acceptable than that of the simple parallel case in Figure 5. This demonstrates that the push-pull configuration serves very well to reduce distortion.

However the push-pull configuration is not always the best choice since there is a trade-off between minimum distortion and maximum available peak output. Figure 5 illustrates that the peak potential available at the maximum output level for the simple parallel case is about 640 V peak. In Figure 7, the maximum available peak potential at maximum output for the push-pull case is about 520 V peak. In some direct-drive applications, the maximum available peak capability is more important than distortion. In other applications, good signal fidelity is the more important parameter. A typical linear amplifier system for direct-drive testing should allow the user to arrange the amplifier elements into the configuration required for testing.

SOURCE OUTPUT IMPEDANCE

Many direct-drive test specifications include a requirement for a specific source impedance. In such tests the applied stress is specified in terms of measured levels appearing at the test object. For example, the actual driven pin is stressed in the case of direct pin injection. The relationship between the potential and current at the point under test is a function only of the load impedance presented by the point under test and is totally independent of the source impedance of the direct-drive source. The specification of a source impedance, however, does have value in some cases where the drive is specified in terms of the source parameters -- such as the Thevenin source potential. In upset testing the source impedance is critical to the proper performance of the unit under test.

Regardless of the ultimate value of the source impedance specification, it is a specification demanded by test designers and must be dealt with. One common source impedance specification is 100 ohms resistive. RF amplifiers are frequently specified for operation into specific loads, typically 50 ohms resistive. However, that specification does not imply that their source impedance is equal to that specified load. Each of the 1 kW amplifiers used in the distortion example above is specified to deliver a rated power of 1 kW when loaded into 50 ohms. However the actual output impedance of those amplifiers is not 50 ohms. Figure 8 shows the small-signal output impedance of those amplifiers as a function of frequency. Demonstrably they are basically 100-ohm output impedance devices. If a single amplifier is sufficient to satisfy the test level requirements, the 100-ohm impedance is well satisfied to about 100 MHz but becomes poor at higher frequencies. If two amplifiers are needed, the 100-ohm requirement is a problem. A parallel combination, either simple parallel or push-pull, provides a 50-ohm impedance while a series combination provides a 200-ohm impedance. In either case, a 2:1 impedance transformation is needed to satisfy a 100-ohm source requirement.

One method of meeting the 100-ohm requirement with the 100-ohm amplifier elements is by using a combination of four such amplifiers. As an example a series combination of two parallel pairs can be used. However, this method results in an amplifier system that has considerably more drive capability than would be required if two amplifiers could provide the needed levels but at the incorrect impedance. The excess capability is only about 3 dB but in the discipline of RF power amplifiers, that is a very significant margin. To increase the available power of an RF amplifier by 3 dB, the amplifier size must be doubled. A conservative amplifier design is certainly an advantage, but the RF power amplifiers are the single most costly subsystem element of a typical direct-drive system. Thus, doubling the amplifier complement simply for the purpose of meeting an impedance specification could be quite costly. In many cases, the amplifiers are defined as having a 50-ohm output impedance (based on the specified load impedance) so that the series combination of two amplifiers has a defined 100-ohm impedance. More precisely, it is defined as 100 ohms to satisfy the test specification, but in actuality it is still 200 ohms. As indicated above, the actual impedance may not be of consequence if the needed test levels can be achieved, but such a source does not meet the exact specification. A rigid output impedance specification is a difficult parameter to satisfy with most pulse power systems. In competitive bidding, meeting this specification of source impedance could have a significant impact on the price quoted. If a specific output impedance is not actually required for the testing contemplated, it should not be included as a specification. However, the output impedance should be documented along with that of the other amplifier performance parameters. If an output impedance is specified, it would be prudent to require that it be physically provided rather than provided by simply definition.

RF POWER AMPLIFIER TECHNOLOGIES

There are two available power amplifier technologies of suitable capacity for direct-drive sources: solid-state and vacuum tube. The solid-state technology is the more contemporary but is not generally a very practical choice for application as a direct-drive pulsed-power source. A solid-state unit has the advantage of no wear out, and since no filament power is necessary, it is slightly more efficient than a vacuum-tube unit. However, a disadvantage of a solid-state amplifier is that it is generally intolerant of high VSWR and reverse power applied to its output. To protect the amplifier from damage, various protection practices are incorporated in the design, but these are often incapable of protecting the unit in a typical direct-drive application. Some level of reverse power feed is not an uncommon occurrence in direct-drive applications since the load almost never matches the source. A large single amplifier might be developed for the application, but the situation would be much the same since the internal structure of the amplifier would have to be configured of many individual elements to achieve the required power levels. Also, a single amplifier would eliminate the versatility of combining different configurations, thus allowing for different test parameters. In general, a vacuum tube amplifier is virtually indestructible with respect to RF abuse -- a very important feature in direct drive applications.

Also, the extremely wide bandwidth required for direct-drive testing, about 18 octaves, is a formidable challenge in an RF power amplifier design. There are, however, a number of commercial manufacturers with products suitable for direct drive applications. In order to achieve the required output level, several power devices (transistors or vacuum tubes) must be combined. However, if they were simply paralleled or combined in series, the effect of the parasitic elements would result in very low cutoff frequency. To solve that problem, a lumped-parameter transmission line is constructed utilizing the individual device parasitics as integral elements of the line structure. That configuration is a distributed amplifier, and it provides a high upper frequency capability with multiple elements.[3] The basic 1 kW amplifier module used in the examples above utilizes 24 4CX250B vacuum tubes in a distributed amplifier configuration. The impedance of the lumped transmission line is not an arbitrary choice; it is determined by such parameters as the individual component parasitics and the desired upper cutoff frequency. Thus the source impedance of typical wideband RF power amplifiers is not 50 ohms. The amplifier output impedance is selected on the basis of other desired features.

SYSTEM CONSIDERATIONS

Another crucial factor in direct-drive testing is safety. The ac power levels required are quite respectable, and the accessible RF power levels are potentially lethal. Obviously the physical security of the amplifier must include appropriate safety hardware. The basic amplifier design must incorporate appropriate interlocks to remove or reduce these test hazards should the chassis integrity be violated. Most importantly, equipment should be installed by a trained electrician in strict accordance with the National Electrical Code[4,5] and only trained personnel should have access to the amplifier system.

Another important consideration is feedback stability. The total gain associated with a linear amplifier system can be relatively high -- on the order of 70 to 80 dB. If feedback paths are present that allow coupling of the output power back into the lower signal level elements of the system, an uncontrolled oscillation can result. In general, such a feedback condition is not damaging to the direct-drive system since it simply delivers maximum output and is typically protected from over-dissipation. Unfortunately, feedback oscillation could destroy the unit under test. Usually, a properly designed direct-drive source is immune to feedback instability under test conditions. However, this feedback problem can occur in cases where the test configuration allows a relatively uncontrolled radiation of the RF signal. In such cases, it is best to place the test object in a screened enclosure to assure stability of the pulsed-power source and to prevent nuisance radiation into the environment.

Losses in the various signal paths are also a consideration in the direct-drive test system. In general, the path losses up to the actual linear amplifier are not too critical since the typical direct-drive system will have sufficient gain margin to compensate for some path loss. However, any loss from the amplifier output to the point of use must be minimized. In terms of gain, a loss of a few dB is not generally considered too serious. However, a loss of 3 dB from the direct-drive amplifier output to the point of use results in the loss of one-half of the amplifier complement. At the amplifier output, significant losses are measured in tenths of a dB. Similarly, availability of margin for excess drive is measured in tenths of a dB. To provide a 3 dB margin would mean that the number of power amplifiers would have to be doubled at considerable cost to the overall project.

AC power distribution is another item that must be considered in direct-drive systems utilizing linear amplifiers. Since linear amplifiers generally operate Class A, their ac input power is independent of delivered output. Also they are very inefficient -- values of 10 to 20 percent are typical. The service capacity for general direct-drive testing utilizing linear amplifiers is on the order of 25 kVA to 50 kVA. This range will provide sufficient capacity for the direct drive system and various other equipment associated with testing. It is best to provide all of the required power for the direct-drive test environment from a dedicated service carrying no other loads. This arrangement preserves the integrity of the power available to the test environment and reduces the possibility of corruption of other equipment powered on the immediate grid. A consistent service supplying only the test environment is also a good safety practice since the feeds for all circuits are very well defined.

Additionally, the thermal load of the linear amplifier system must be considered in the facility configuration. Most of the ac mains input power is dissipated as sensible heat (as opposed to latent heat). A typical heat load may be on the order of 100,000 BTU per hour -- roughly the output from a moderate home heating plant; some provisions for removing this heat is required. Both air cooling and liquid cooling are available in commercial amplifier systems. Air cooling is almost a necessity in portable systems while liquid cooling is suitable for permanent installations. However, if coolants other than untreated water are used, environmental and personnel hazards are introduced. Oil cooling presents a potential fire hazard. Air cooling provides a low-maintenance cooling system, but the local discharge of heat and high sound level of the air movers must be considered. In a laboratory environment, the heat load may be exhausted outside the facility with supply air provided from within the laboratory environment. The typical sound level is not a personnel hazard, but it is sufficiently high to obscure background sounds. If a screened enclosure is used in the test environment, it is most convenient to place the test object inside the screened volume and the amplifier system external to the volume. Thus, the amplifier heat load does not then have to be handled through the enclosure.

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der of the present injection procedure.

The CS13 calibration procedure requires a number of corrections and modifications. The 18 AWG wire loop must be replaced with a low inductance network, which should incorporate provisions for the short and open circuit calibrations. The short circuit current is measured with a current probe as before. However, the open circuit voltage should be measured on an open circuit with a device designed to do so -- a voltage probe. The probe used should have a 100:1 attenuation, and a bandwidth of at least 200 MHz. Both calibrations can still be performed, but when injecting, the current setting is the starting point, and the output is increased until the current limit or the voltage setting is obtained.

Other important concerns to be addressed in the test plan writing stage and in future revisions for both test methods include precisely detailed test setups, especially grounding techniques and cable configurations. Current probes should be specified to have a flat frequency response in the range over which they are used. Good measurement practice dictates that the measuring device should have an input bandwidth of at least twice the highest frequency to be measured. Since the fastest signal involved in MIL-STD-461C/462 EMP testing is a 100 MHz transient, the oscilloscope used to measure this signal must have at least a 200 MHz bandwidth. If a digitizing oscilloscope is used, its sampling rate should be at least ten times the highest frequency to be measured, or 1 GSa/s. The sampling rate should also be variable so that the low frequency transients may be recorded. Obviously, if a 10 kHz signal is sampled at 1 GSa/s the oscilloscope's memory will be filled before the entire wave form is captured.

Although many serious problems and omissions exist, CS12 and CS13 tests can be performed before the necessary revisions are made if these problems are addressed at the test plan writing stage. The plan's author will need a thorough understanding of EMP testing and an appreciation of the guidelines set forth in this article. Ultimately, the necessary revisions must be incorporated into the existing test procedures to form a wholly realistic and meaningful test specification. ■

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CONCLUSIONS

The linear amplifier is a very attractive pulsed-power source for many direct-drive applications. Typically available units provide drive levels meeting essentially all the needs of direct pin-injection testing, many of the bulk-drive requirements, and some of the surface-injection needs. The linear amplifier allows the use of essentially any arbitrary waveform and wide variation of individual waveform parameters. The use of complex waveforms is simplified with generation at low levels with linear amplification to required drive levels. However, the basic cost of a linear amplifier is substantially higher than that of the more common energy storage pulsed-power sources.

There is a compromise between output level and waveform fidelity. At output levels approaching the specified limits of an amplifier, distortion will generally be quite noticeable. Operation of the amplifier in a push-pull configuration will improve the waveform fidelity, but will result in somewhat lower peak output drive than available from a simple parallel configuration.

In the development of a testing program utilizing a linear amplifier source, several system-level considerations must be addressed. Personnel safety must be a primary consideration. Care must be exercised to control feedback instability and screening may be necessary. A well configured ac power distribution system is required and provisions for heat removal must be included. ■

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