Test Requirements: Selecting the Optimal AC Power Source Technology for your Application

Linear or Switch Mode Technology considerations and trade-offs

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Abstract – This paper discusses the difference in performance between linear topology programmable AC power sources versus PWM switch mode programmable AC power sources and the implications of these performance differences on various AC power development and test applications.

Keywords – AC Power Source; Programmable AC; Linear; Switch Mode; Applications; Performance

I. Introduction

Understanding the capabilities and differences of linear and pulse-width modulated (PWM) AC power sources is especially helpful to system integrators and specifying engineers. Knowledge of the differences in available technologies allows them to decide which type of AC power source is best suited for the application.

The selection of an AC power source should be based on more than basic specifications values of voltage, frequency and current or power. Selection based on incomplete requirements is risky at best. In fact, ignoring real-world requirements may lead to disappointment with product performance, test results or both.

Critical operational capabilities include bandwidth, current and voltage regulation. Other application-specific requirements are size, weight, operating temperature and cost. For many mid-range applications, either linear or PWM switch-mode technology will provide satisfactory performance. In other more stringent applications, only one of the two technologies will best meet an operator's particular needs.

This paper will provide an overview of both linear power amplification and PWM Switch mode designs. Pros and cons of each approach and the implications of each on power quality and specific types of loads will be compared side by side.

II. The Need For AC Power Conversion

Within the United States, commercial mains-supplied AC power is convenient, reliable and usually stable. By intent, mains-supplied AC is inflexible. However, many ATE tests require a wide range of controlled voltages and frequencies. Other tests must support startup surges and the measurement of harmonic currents. Utility AC power is subject to induced noise and perturbations caused by diverse loads on the grid. It is not always easy to recognize the limitations of utility AC power. Often, utility AC is neither flexible enough nor noise-free enough to allow precision measurements. Unpredictable variations make repeatable controlled tests impossible. Precision AC power source becomes an obvious solution.

A well-instrumented AC power source can deliver precisely managed power to fully characterize a unit under test. The AC power source may be used to present a range of voltages and currents to determine steady-state power needs. In addition, transients, harmonic waveforms and other voltage perturbations may be applied. These features support limit-testing and verification of operational extremes for a unit under test. Using the AC power source's built-in measurement features, loading characteristics of the unit under test can be analyzed.

Many ATE systems need precision controlled AC power to energize the unit under test. In particular avionics equipment will require AC power other than 50Hz or 60Hz so using local utility power is not an option. Even for non-avionics test applications, depending on local utility power is a risky design choice, especially in parts of the world where utility power is not a stable and predictable as it may be in more developed countries.

Equally important is avoiding the introduction of electrical noise into an ATE system as noise – once injected by a switching AC power source for example – can be very difficult to eliminate. Avoiding the introduction of noise sources through the use of a linear AC power source is far preferable.

III. Load and Performance Testing Requirements

A rugged power source is essential for use in a production test environment. A production source must be convenient to use. It must deliver the prescribed wave shapes, frequencies and power to units under test. For product development engineering use or general-purpose testing, ease of reconfiguration is important. Reconfiguration capabilities include: voltage range, frequency range, number of output phases and execution of pre-established voltage limit tests. However, even with very simple applications, the dynamic power characteristics of the equipment under test must be considered. Many loads are not resistive. As a result, an applied voltage and load current may not be in phase. For the purposes of this paper, out-of-phase operation is identified as low power factor. (By definition, power factor is the ratio of real to apparent power, but it can also be observed as the phase angle difference between voltage and current waveforms.) Modern day loads however are commonly non-linear in that they have rectifier inputs resulting in a power factor of less than 1.0. Additionally, a load may demand peak current many times greater than that predicted by average or steady state power consumption. A high peak current condition can be defined by the current waveform crest factor, which is the ratio of peak current to an AC waveform's RMS current. Finally, in many applications, the selected AC power source must provide a reservoir of energy. Reserve energy is necessary to meet startup surge current requirements without distorting the voltage or ride-through capability in locales where the grid power may not be fully stable.

IV. Fundamentals of Solid-State AC Power Conversion

Electrical power converters transform electrical energy in one form into electrical energy in another form. An AC power converter in its simplest form can be thought of as a black box with only input and output terminals. From this simplistic perspective, the input-to-output process appears to be a single AC-to-AC power conversion stage. This model would apply to a transformer which can convert voltage and phase relationships but not frequency. To accomplish frequency conversion, at least a two stage conversion topology is required. Internal power management involves AC-to-DC conversion at the input (Rectification). The output requires DC-to-AC conversion (Inversion). Any wide-range AC-to-AC power source includes intermediate processes of AC-to-DC and DC-to-AC conversion. These are not academic considerations; the efficiency of each conversion stage has implications for weight, size, temperature rise and cost.

More efficient conversion processes result in smaller, lighter-weight, and cooler-running units. Less efficient conversion processes result in larger, heavier, and possibly hotter-running units. It follows that the efficiency of each power conversion stage is a significant factor in determining size, weight, and temperature rise.

Solid-state AC-to-AC power conversion can result in a reliable source of precision operator-controlled AC power. The AC mains provide basic raw AC power. The converter delivers a tightly controlled synthesized waveform at the prescribed voltage, frequency, phase angle and power level.

Fig. 1 illustrates how noisy unregulated AC power is converted to DC. Simultaneously, a controlled low-level precision waveform is generated by an oscillator or digital synthesizer within the power source. The low-level oscillator's signals are amplified, using the converted DC as an energy source. The result is a stable well-defined high-level AC voltage with prescribed wave shape and frequency. This is true for both linear amplifiers and PWM switch mode amplifier designs.

The reason for using either linear or switching technology depends on the specific application. For example, consider a non-sinusoidal load current with a high crest factor. This load requirement is best satisfied by a linear amplifier. High-power linear amplifiers can deliver peak currents (high crest factor) with undistorted voltage. For another example, consider a linear load with a very low power factor (large phase shift). Low power-factor requirements are more easily satisfied by PWM switch-mode amplifiers as no reactive power has to be dissipated by this type amplifier.

V. Performance Selection Criteria of an AC Source

One must consider the individual testing requirements to determine whether linear amplification or PWM switch-mode operation provides the best possible performance for the application. In addition, careful evaluation of requirements will determine which of the two technologies provides the more cost-effective solution. Operational requirements include:

- Frequency range
- Load ttransient response
- Current crest factor capability
- Voltage distortion
- Output impedance
- Power factor loads
    - Non-linear
    - Reactive
- Startup surge current or inrush current capability
- Size
- Weight
- Cost

VI. The Case for a Linear AC Power Source

Linear AC power sources produce low-distortion output waveforms. Linear amplification is achieved by using non-saturating methods. The advantage of linear amplifications is faithful reproduction of the (synthesized) oscillator waveforms. Furthermore, linear AC power sources feature wide-bandwidth,

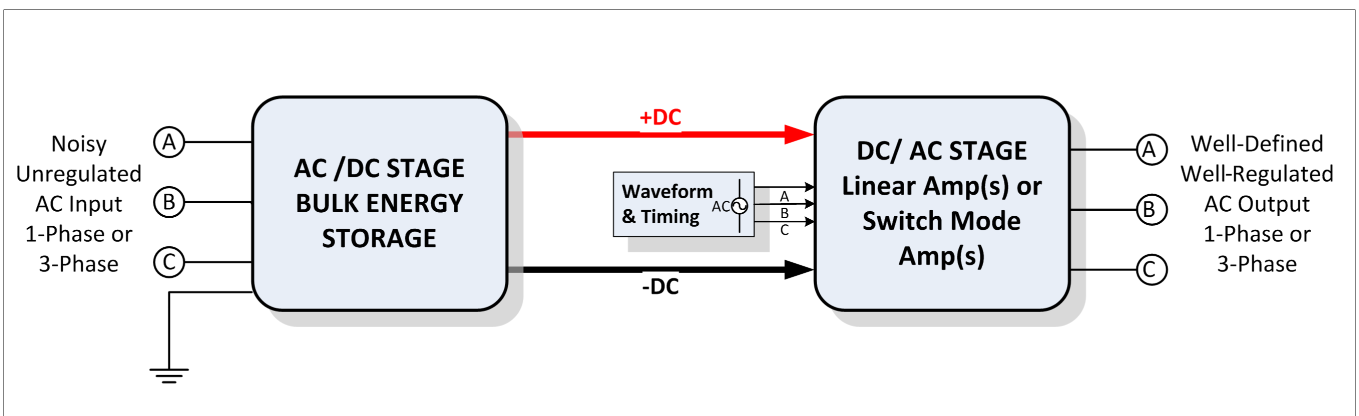

Fig. 1. Fundamental AC-to-AC Power Conversion

excellent transient response and the lowest possible output impedance.

Linear amplifiers do have a disadvantage of being less efficient. Types of linear amplification include class A, B and AB. The letters refer to signal conduction angle. Class A linear amplifiers typically operate at less than 50 percent efficiency. Class B or AB can achieve peak efficiencies greater than 50 percent. As a consequence of low operating efficiency, size and weight can be an issue when deploying linear power sources, especially at higher power levels.

A. Characteristics of Linear Amplifier Technology

The advantage versus drawbacks of a linear AC amplifier based AC power source can be summarized for comparison as follows:

Advantages

- Very low output distortion
- High full power output bandwidth
- Very high small signal bandwidth for modulation and harmonics applications
- High crest factor handling for wide range of loads without voltage distortion
- Ability to absorb energy fed back from the unit under test
- Wide range of active output impedance control

Drawbacks

- Power derates for low power factor loads
- Higher temperature operation due to class A, B, and AB amplifier inefficiencies
- Larger size due to higher component count and heat sinking requirements
- Higher weight due to higher component count and heat sinking requirements

B. Basic AC-to-AC linear amplification power conversion

Fig. 2 illustrates the basic operation of a linear AC power source. At the input, one-phase or three-phase AC is converted to DC. Following rectification, filtering removes AC-ripple, any broadband noise, and intermittent transients. Energy Restorage overcomes the effects of dropouts and line sags. The stored energy is subsequently used for powering the output amplifier. Simultaneously, a low-level controlled waveform is generated by an oscillator in the power source. Modern AC power source controllers use digitally synthesized waveform generation. Consequently, synthesized wave shapes are identical, regardless of output frequency and extend beyond just sine waves. Finally, the waveform is amplified to the required level of voltage and power by the linear amplifier stage. When required to manage complex loads, the linear amplifier's output impedance can be fixed or managed through active real-time feedback control. Finally, the linear amplifier's wide bandwidth is ideally suited to delivering faithfully shaped complex waveforms or very low distortion sine wave output. The lack of a switching power stage eliminates the need for any output filtering at the output of the linear AC source.

VII. The Case for a Switch Mode AC Power Source

Switch-mode AC power sources use a combination of linear and non-linear methods to achieve waveform amplification. Methods include pulse-width modulation, non-linear amplification and low-pass filtering. Switch-mode amplifiers are highly efficient because the H bridge power devices are either fully on or fully off. Consequently, less power is dissipated (lost) in the amplifier than for linear amplifiers with full-time conduction cycles. Switch-mode amplification is called class D. Class D amplifiers provide an output with high harmonic content. An output stage low-pass filter is required to reduce high voltage distortion and output switching noise. However, no amount of filtering can completely eliminate these artifacts of a switching topology.

A. Characteristics of Switch Mode Amplifier Technology

The advantage versus drawbacks of a switch mode AC amplifier based AC power source can be summarized for comparison as follows:

Advantages

- Higher efficiency power conversion results in reduced temperature operation
- Higher efficiency power conversion allows smaller heat sinks thus reducing size and weight
- Reduced component count can result in lower cost
- Ability to drive low power factor loads without derating

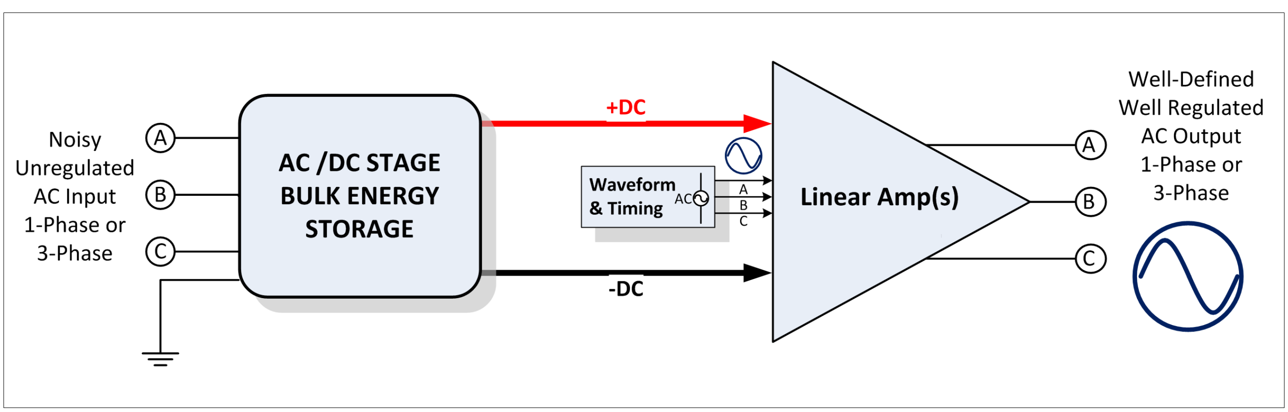

Fig. 2. AC to AC Linear Amplification Power Conversion

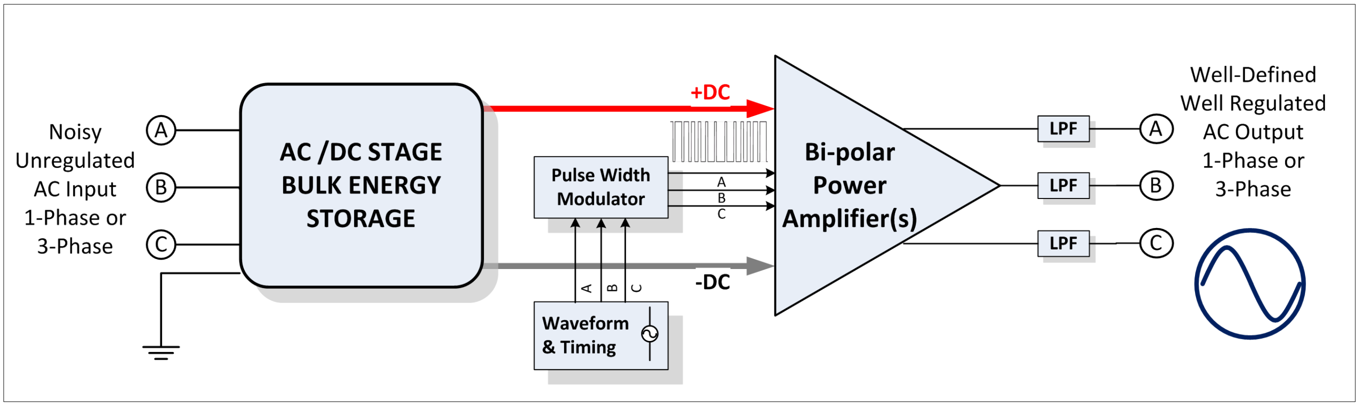

Fig. 3. AC-to-AC Switch-Mode Power Conversion

Drawbacks

- Higher output voltage distortion
- Much higher output switching noise on AC source output can affect sensitive systems
- Lower full power output bandwidth
- Considerably reduced small signal bandwidth for modulation and harmonics applications
- High crest factor loads tend to cause voltage distortion
- Output filter stage of switch mode amplifier interacts with EUT impedance impacting phase margin
- Higher output impedance due to output filter and reduced dynamic output impedance control range

B. Basic AC-to-AC non-linear (switch-mode) power conversion

Fig. 3 illustrates the operation of an AC-to-AC switch-mode power source. Input power processing and oscillator signal generation are identical to those described earlier. However, for switch-mode conversion, the low-level analog signal is not sent directly to a linear amplifier. Rather, it is sent to the input of a pulse-width modulator. The pulse-width modulator operates at a free-running frequency many times greater than the highest frequency in the input waveform.

With zero analog signal amplitude input, the output of the modulator is a rectangular wave with equal positive and negative periods. Consequently, for zero input, the output of the low-pass output filter (Fig. 3) is exactly zero volts. However, as the width of the modulated pulses follow the polarity and amplitude of the input signal, the filter's output becomes an amplified version of the oscillator input signal. Because the output is derived from pulse-width samples, there is a larger fractional percentage distortion than with a linear class A, B or AB amplifier. However, the output stage efficiency is much greater than for linear amplifiers, typically 80 percent or higher. Lower power loss in the output stage results in cooler operation and smaller size heat sinks.

VIII. Load Power Factor

Load power factor can impact the choice of AC source in different ways. On the one hand, linear AC power sources are not optimal when driving very low power factor loads as - although little true power is delivered to the load - considerable energy has to be dissipated in the power source's heat sinks. For this reason, linear AC sources generally have a power factor versus current capability rating profile like the one shown in Fig. 4. The chart shows the phase current for a 3-phase 6kVA AC source.

Note that the unit is rated for 16A current for loads with power factors between 1.0 and 0.7. Most non-linear, non-power factor corrected loads have power factors of at least 0.65 and many EUT's use some form of power factor correction to increase power factor close to 1.0 so this limitation has few

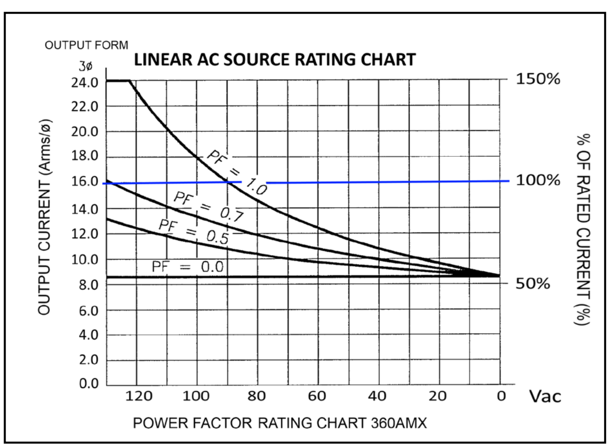

Fig. 4. Linear AC Source Rating Chart

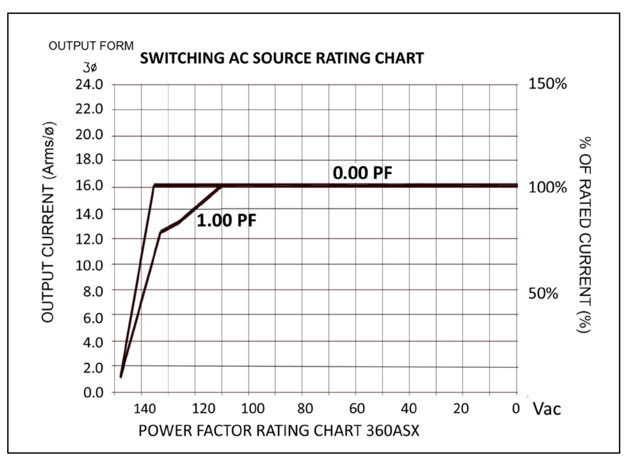

Fig. 5. Switching AC Source Rating Chart

practical limitations. For loads with a power factor of 1.0, up to 150% of rated current can be delivered by the linear AC source. For zero power factor loads, a linear AC source needs to be over-sized if the operation is continuous. The linear load can still deliver full current for short periods of time however.

A switch mode AC power source can typically drive loads down to 0.0 power factor without any current derating. This includes pure capacitive or pure inductive loads. An example of a switching AC source rating chart is shown in Fig. 5 for comparison. This chart is for the phase current of a 6KVA switching AC power source with the same 16A nominal current rating. Note that only a power limit derating occurs for loads at power factor of 1.0 at higher voltage levels.

However, there are other factors to consider other than maximum current. Since linear loads have no output filters that can interact with any load capacitance or inductance, they are unconditionally stable and can drive any power factor load from zero to one, leading or lagging. Switch mode AC power sources on the other hand can become unstable even when driving loads with only small amounts of reactance. This is caused by the load itself becoming a part of the output filter network and adversely impacting the filter dynamics. Under the wrong conditions, this can result in oscillation and amplifier damage. Since AC power sources are general purpose instruments, stable operation under all conditions can be difficult to predict.

IX. Comparison of Features and Capabilities

Table I lists typical applications for AC-to-AC power sources. It is seen that linear technologies provide superior performance for some testing applications. However, PWM switch-mode technology excels for other applications. The conclusion is that one must carefully specify the application.

Table II lists generic benefits of each of the two technologies. It is seen that no single technology excels in all areas. A full understanding of all these requirements is in order while avoiding over-specifying.

Table I: Typical AC-to-AC Power Source Applications

Application	Optimal Choice
DC supply ATE tests	Linear
400Hz, synchronous ATE system	Linear
R&D power line disturbance tests	Linear
Watt-hour meter testing	Linear
Power line disturbance tests	Linear
Production life tests (frequency conversion)	Switch-Mode
Circuit breaker tests	Switch-Mode
Safety compliance tests	Switch-Mode
Commercial appliance test and burn-in	Switch-Mode
Motor performance and safety tests	Switch-Mode
Note: In a particular situation, either amplifier type may be more appropriate.	

Under less demanding performance conditions, switch-mode sources are typically more cost-effective. For the absolute highest performance, linear amplifiers are more capable. However, there is no single-parameter right-or-wrong solution when it comes to selecting a linear or a switch-mode AC power source. The appropriate solution depends entirely on the full set of requirements, including:

Table II: Extreme Pros and Cons of Each Technology

Feature / Capability	Optimal Choice
Highest amplifier efficiency	Switch-Mode
Lowest operating temperature	Switch-Mode
Lowest weight	Switch-Mode
Smallest size	Switch-Mode
Lowest cost	Switch-Mode
Low-power factor handling	Switch-Mode
Lowest harmonic distortion	Linear
Highest small-signal bandwidth	Linear
Highest large-signal bandwidth	Linear
Active impedance control	Linear
Highest crest-factor	Linear
Highest startup surge current	Linear

- Output voltage range
- Output current requirements, including inrush and overload
- High peak current for non-linear (high crest factor) loads
- Phase angle of output current (power factor)
- Accurate replication of custom or high harmonic waveforms or both
- Fast transient capability
- Amplifier output voltage distortion
- Amplifier output impedance and control
- Size, weight, and efficiency limits
- Environmental needs and limits
- Performance versus price considerations

X. Conclusion

In conclusion, given a set of realistic requirements, one can make an objective decision about which technology provides the appropriate solution. When the exact requirements are not obvious, knowledgeable vendor application support is often the best path to success.

Acknowledgment

Authors like to acknowledge the contributions of many loyal customers over a long period of time who provided information and feedback on the use of our programmable AC power sources – both linear and switch mode – in their specific applications and enable us to continuously refine and improve our products for optimal performance under a wide range of AC power applications.

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