This "class-D" switching mode technique will permit solid-state circuits to exceed power capabilities of tubes without heatsinking at nearly 100% efficiency. Useful for audio, r.f., and control applications.

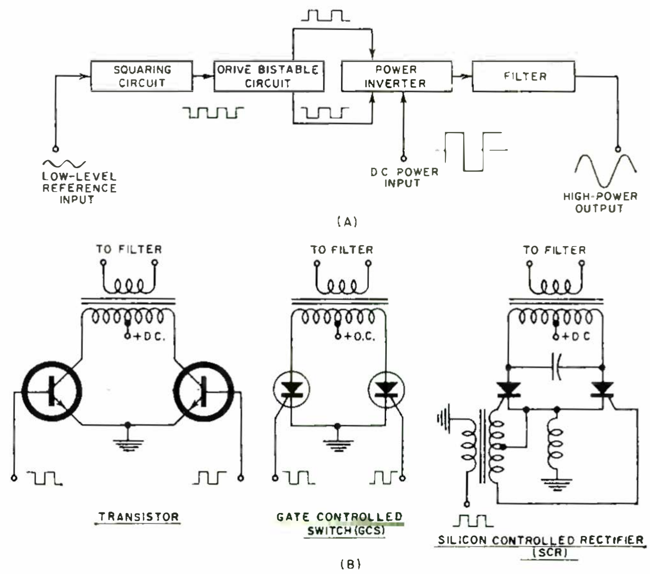


Fig. 1. (A) Constant-amplitude, single-frequency system. (B) Various semiconductors can be used in inverter stage.

AMPLIFICATION USING SWITCHING TECHNIQUES

By DONALD E. LANCASTER

THERE is a new way to amplify signals. It violates every one of the rules of conventional class-A, B, or C amplifiers in that it allows linear amplification of any signal at practically 100% efficiency. This new concept may drastically alter every electronic system from hi-fi amplifiers to complex military systems. It will allow integrated circuits to deliver substantial power to a load without the need for heatsinking. It will allow solid-state systems to meet and exceed the very high power capabilities still the sacred preserve of the vacuum tube. As an example, one unit now available on the market is an r.f. power amplifier that delivers over a kilowatt of output with an efficiency of over 95%.

Other ramifications of the technique, which has been called "class-D amplification," are almost hard to believe. All of the normal amplifier concepts are totally absent. Frequency response may be made essentially flat from d.c. to some precisely specified upper cut-off frequency, with the phase behaving just as well. Linearity of the semiconductors employed is no problem at all. There is no worry over non-linearity or crossover distortion, no problems with drive matching and balance. In fact, silicon controlled rectifiers (SCR's) or gate controlled switches (GCS's) can be used instead of the more familiar transistor. Use of these higher voltage devices as output semiconductors allows simple, direct-line-operated power supplies, eliminating the bulky power transformer and expensive high-current filter elements. In addition, the gain of an SCR or GCS is very much higher than ordinary transistors due to the regenerative turn-on mechanism. With these regenerative devices, fewer stages of amplification are needed in order to attain a given level of power output.

Basic Principles

The key to class-D operation is quite simple: *All of the amplifying stages in the system are run switching mode, that is, they are always either completely "on" (saturated) or completely "off"*. In neither of these states does the switching device consume any significant supply power, hence the possibility of near 100% efficiency.

There are two basic types of class-D systems, those that produce only a single-frequency (not necessarily fixed) constant-amplitude output; and those that handle any amplitude and frequency input signals over a wide range while providing linear amplification.

Let us consider the simpler system first. Fig. 1 shows a basic class-D system of the constant-amplitude type. The input signal consists of a sine-wave reference frequency at a very low level. Typical would be the output from a crystal frequency standard or a reference oscillator. This input signal is squared up to produce a square wave at the reference frequency. The reference signal, in turn, drives a bistable circuit that produces two high-level square-wave outputs. One is in phase with the input signal, while the second forms the complement, or the 180° phase-shifted replica of the input.

These two drive signals are used to drive a push-pull transformer-coupled output stage. This stage is nothing but a driven high-power inverter. First one semiconductor, then the other, is turned "on," the opposite semiconductor turning "off" as its mate turns "on." The alternating current flow will induce a square wave in the transformer secondary. This square wave will be a very high power signal of precisely the same frequency and phase as the input reference.

Any square wave consists of a fundamental sine wave and series of diminishing odd harmonics. If a low-pass filter is introduced between a square wave and its load, only the fundamental frequency component, an ordinary pure sine wave, will be passed provided the cut-off frequency of the filter is above the fundamental and below the third harmonic. All of the square-wave input power will appear as a sine wave at the output, since the higher order harmonics will be looking into a very high impedance at the input to the filter.

Note that this system is *not* a resonant one and that it will easily pass a wide band of frequencies, as long as the fundamental frequency is below the cut-off of the filter and the third harmonic is above the cut-off point. Using sharp filters, a 2:1 frequency spread of input signals may be accommodated. This is a most important advantage over the normal class-C system. Another important advantage is the ratio of peak-to-average current in the output semiconductors. The peak-to-average ratio is only 2 in the class-D system, while it can approach several thousand in class-C operation. Because the semiconductors do not have to handle brief, extremely high current pulses, higher actual efficiencies may be realized.

Since the output works well over a band of frequencies, the system will handle frequency-modulated signals, carrier-shift industrial communications, swept radar waveforms, and other wide bandwidth signals. As the output power will be a constant determined only by the load resistance and the supply voltage employed, the class-D system is also an effective amplitude limiter, for no variation in the strength of the input signals will appear at the output of the particular circuit that is illustrated.

Applications of Fixed-Amplitude Systems

Fig. 2 shows the output stage of the previously mentioned r.f. carrier generator, intended for prime c.w. power output in the 10 to 500 kc. range. This all-solid-state system puts out 1200 watts of carrier with an over-all efficiency of 95% and with all spurious outputs attenuated by 50 decibels. Similar vacuum-tube systems at best attain an efficiency of less than 70%, considering all losses.

Motor controls are another application of a single-frequency, constant-output class-D amplifier. By using class-D techniques, it is possible to precisely vary or hold fixed the speed of any a.c. motor. Since the speed of an a.c.-only motor is a function of frequency and not the applied voltage, all the normal control schemes (*e.g.*, autotransformers, rheostats, conventional SCR controls) will not effect control and can, in certain instances, damage the motor. A class-D system varies the applied frequency to the motor, allowing precise control of synchronous, induction, or hysteresis motors.

Fig. 3 shows a typical scheme. Here a low-power control sine wave of the desired frequency is clipped into a square wave and used to drive a power inverter. The inverter output, in turn, powers the motor. A filter is not normally required since the motor's inductance effectively filters the higher order harmonics of the square wave. The values shown provide a 200-watt, 400-cps power source.

This technique is useful in three major ways. It may be used to maintain a constant motor speed in light of a varying or unpredictable supply frequency. This problem often crops up in aircraft systems, where the supply frequency can often be far too unstable for such constant-speed drives as are used in tape-recording systems and precision servos.

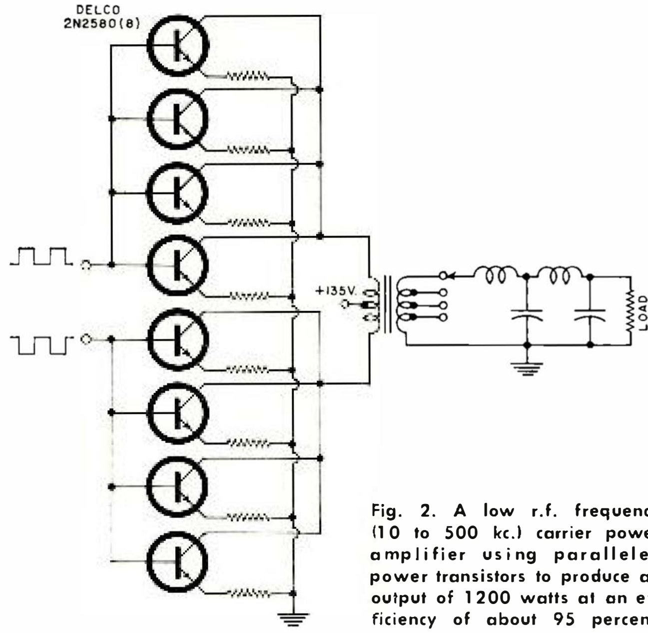


Fig. 2. A low r.f. frequency (10 to 500 kc.) carrier power amplifier using paralleled power transistors to produce an output of 1200 watts at an efficiency of about 95 percent.

Usually a tuning fork or a synchronized reference signal is used for the low-level drive.

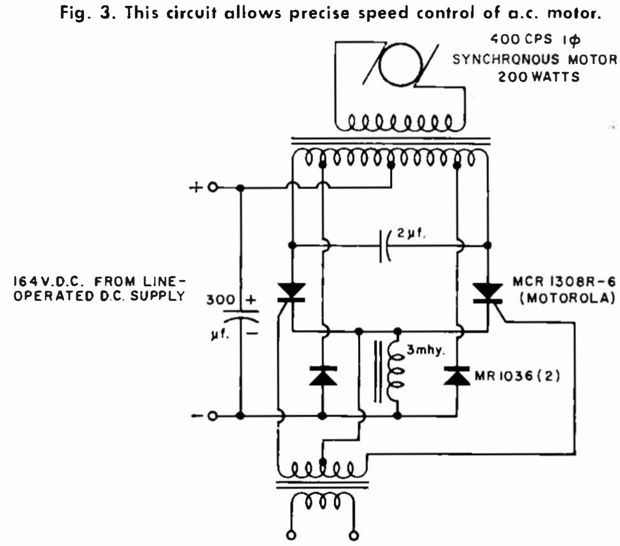
Alternately, we may purposely wish to change the speed of a motor, perhaps to control a fan, an industrial drive, or a drill press or a table saw in the home shop. A small variable frequency audio oscillator forms the reference that is amplified to provide the motor power. Feedback may be easily used to maintain any desired set speed of an induction motor using this technique.

All the power inverters operate from a d.c. source. Usually, the available 60- or 400-cps power is rectified and filtered to provide the necessary motor power. The fact that the inverter is, in reality, d.c.-powered allows a.c.-only motors to be run from a d.c. source. Such a.c.-only motors are generally much lower in cost than d.c. designs and much more maintenance-free since they have no brushes or commutators that require attention. Further, there is no brush wear, brush noise, or any danger of sparking, and most important of all, there is no radio-frequency interference generated by an a.c. induction motor.

Linear Class-D Systems

The linear class-D amplifier must not only amplify a single frequency to some specified power level, but it has to simultaneously handle many frequencies and amplitudes,

Fig. 3. This circuit allows precise speed control of a.c. motor.



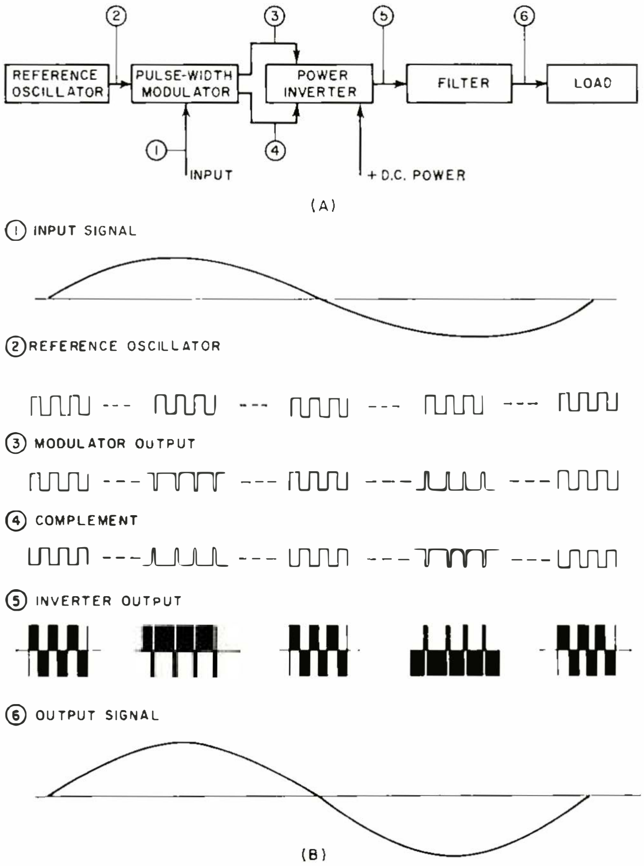
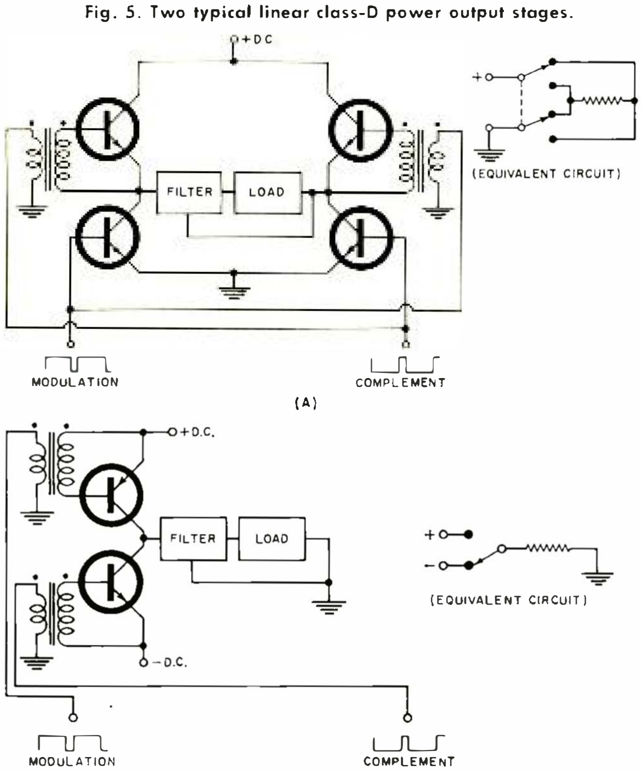


Fig. 4. Block diagram and waveforms for linear class-D circuit.

providing an output that linearly follows the input signals. Square-wave "off-on" techniques are again used, except that in the linear systems, the frequency of the square waves is much higher than the signals to be amplified. The input signals are used to *pulse-width modulate* the square-wave reference. This is done in such a way that the ratio of "on" time to "off" time is a linear function of the input signal, but the period (the sum of the "off" time and the "on" time) is a constant, independent of the signal.

Fig. 5. Two typical linear class-D power output stages.



Some typical waveforms are shown in Fig. 4. Here the input signal is a sine wave but, in reality, any waveform works as well. This input sine wave modulates the square-wave reference. At the positive peaks of the input sine wave, the reference output is "on" very much more than it is "off," and at the negative signal peaks, the reference output is "off" very much more than it is "on." For in-between signal levels, the ratio of "on" time to "off" time is a precise function of the signal amplitude. At the "zeroes" of the sine wave, the output is a symmetrical square wave with equal "on" and "off" times.

The output of this circuit, together with a complementary signal is used to drive a power inverter. Typical output stages are shown in Fig. 5; these are a full-wave bridge circuit for single-ended supplies and a two-semiconductor switching type that requires dual supply voltages. The load waveforms are the same in either case and appear as the bottom two waveforms of Fig. 4B. At the input to the filter, the current flows for equal times to the right and the left, and the output power, averaged over an entire period is precisely zero in the case of no input signal or the zero of an input signal. With positive signal inputs, the current flows to the left (through the filter and load) for a longer time each cycle than to the right. The average value, over a cycle, results in a positive output to the load. Similarly, with a negative signal input, the current flows to the right for a longer time each cycle than to the left, resulting in a negative output to the load averaged over each cycle.

The averaging (or integrating) is done by a low-pass filter that responds only to the average energy in each cycle. This is done by choosing the cut-off frequency of the low-pass filter well below the reference frequency but far enough above the input signal frequencies so that they are not attenuated. The net effect of the filter is to produce an output voltage that faithfully follows the input signal, amplified many times at very high efficiency.

The frequency response of this technique varies from d.c. to half the sampling or reference frequency. No matter how slowly the input signal is varying, the output of the inverter is always the same reference frequency, pulse-width modulated to form a "lopsided" rectangular wave in proportion to the input. The d.c. amplification takes place when there is no change from cycle to cycle in the "width" of the modulation signal.

The upper frequency limit is precisely one-half the sampling frequency. This is dictated by a fundamental theorem of sampling mathematics that states that at least two samples per cycle of any signal must be taken to fully characterize that signal. Frequencies above half the sampling frequency appear as noise at the output: it is thus desirable to sharply low-pass-filter the input at a frequency somewhat less than half the reference frequency.

Practical Limitations

There are several practical limitations to class-D systems, some of which have precluded the use of these techniques with vacuum tubes and earlier solid-state devices. This is why such a relatively obvious technique is only today feasible.

The semiconductor switches must be fast and efficient. Considerable power is dissipated during the switching interval. For high efficiency, the total switching time must be very small compared to the reference frequency period. For ordinary SCR's, the upper limit is around 20 kc. for the reference, resulting in a 10-kc. maximum signal bandwidth. Premium SCR's will work to 100 kc., while the somewhat faster GCS's and four-layer diodes are useful to 200 kc. with a resultant d.c. to 100 kc. signal bandwidth. Transistors may be used as high as 600 mc., but at reduced power levels, lower gains, and usually lower supply (*Continued on page 82*)

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voltages. The requirement for a high-level continuous-drive signal when using transistors largely offsets the reduced switching time losses at lower frequencies.

The low losses of class-D allow a substantial increase in the amount of power that can be controlled without the use of heatsinks. As an example, a TO-5 packaged semiconductor can dissipate one watt of heat into a 25°C ambient without any damage. If a class-A linear amplifier is built out of two TO-5 heatsinkless transistors, the maximum dissipation will be two watts, and the most output we could possibly hope for would be one watt, due to the 50% theoretical maximum efficiency of class-A operation. Now, if a class-D amplifier is built out of two TO-5 can SCR's operating at a low reference frequency, each SCR will be able to control 1.5 amperes at 400 volts, or 600 watts. The pair can, in theory, control 1200 watts of load power.

Using conventional techniques, we have built a heatsinkless one-watt amplifier. Using class-D techniques, we have built a 1200-watt amplifier in the same space with the same heatsinking. Naturally, we need a considerably heftier power supply for the kilowatt amplifier.

A second class-D limitation is distortion. Since the input signal effectively disappears shortly after entering a class-D system and does not appear again until the output, all the normal forms of distortion are simply not possible. Unfortunately, there are two new forms of distortion that must be dealt with. One results from the finite switching times and other device limitations, while the second is fundamental intermodulation distortion between the signal and sampling frequencies. The former is a much more severe problem and can be eliminated by better circuits. Typical distortion figures run from 1 to 20%. For high-fidelity applications, the distortion can be substantially reduced by using a reference frequency much higher than the highest signal frequency of interest. For low-distortion 20-kc. response using today's circuits and techniques, a reference frequency of 150 to 200 kc. would be required. This frequency is well above the audio range so that the usual r.f. techniques must be employed in the audio amplifier. Added to this is the complexity of an accurate, distortion-free pulse-modulation circuit.

The constant-amplitude systems have one or two additional limitations. Should the drive disappear in these simpler systems, very high fault currents would shortly damage either the output inverter or the power supply. Some form of drive failure protection, or at least very fast-acting circuit breakers must be provided with this type of design. There is also a limit to the range attainable when controlling the speed of an a.c. motor due to the motor's impedance changing with frequency. At frequencies much lower than the design frequency, the motor draws heavy current. At frequencies well above the design frequency, the motor's impedance is so high that very little current flows, and no mechanical power reaches the shaft. Because of this, the class-D controls are effective only over a 2:1 or, at best, a 3:1 speed range.

Applications

The applications for such devices are quite numerous. High-gain, high-power integrated circuits are practical using this technique, allowing extremely low power consumption of the output stages of transceivers or hand-held units. Battery current would be drawn only on a demand basis, greatly prolonging operating time and allowing smaller batteries to be used.

Home high-fidelity and commercial sound systems will benefit. The high gains, absence of heatsinks, transformerless design, and simplified line-operated supplies should reduce the manufacturing cost. The reduction of size and weight and the greatly reduced supply power requirements will provide important advantages in portable public address equipment, especially mobile systems.

We have already seen how the fixed-amplitude systems may be used for r.f. carrier generation, either FM or c.w., for commercial broadcasting. These same techniques are useful for ultrasonic power generation and sonic testing. Similar principles allow precise speed control and direct current operation of any a.c. motor.

The linear class-D amplifiers will allow high power amplitude-modulation signals for commercial AM broadcasting stations, radar and identification devices, and other high-power r.f. applications. They are also ideal for superpower audio amplifiers, 1-kilowatt plus units, for sirens, plant-wide communications systems, outdoor chimes, and environmental shock testing.

Perhaps in the near future we will see a good many commercial products introduced to the market that make use of this powerful new amplification technique.

(Editor's Note: This article is not intended to describe a construction project. We have no further information on any of the circuits described, parts values, or parts availability. Construction details on circuits of this type for audio use have been published. However, those that we have examined are quite complex and do not yet have the fidelity of performance required for hi-fi applications.) ▲