CHAPTER 11.5
HIGH-POWER AMPLIFIERS

Richard W. French, Clayton R. Roberts

THERMAL CONSIDERATIONS

A problem common to all high-power amplifier and oscillator equipment is removal of the excess thermal energy produced in the active devices and other circuit components so that operating temperatures consistent with reliable performance can be maintained. Available cooling methods are radiation, natural convection, forced convection, liquid, evaporative, and conduction. Radiation and evaporative cooling depend for suitable operation on a rather high temperature for the device being cooled and are thus generally restricted to use with vacuum tubes. The remaining methods are suitable for use in both solid-state and vacuum-tube systems.

HIGH-POWER BROADCAST-SERVICE AMPLIFIERS

Transmitters for amplitude modulation broadcast service may employ high-level (plate) modulation or low-level (grid or screen) modulation of the output stage or modulation of an intermediate stage, followed by linear amplification in the following stage(s). Generally, the last approach is used in very-high-power transmitters, because of the difficulty and expense in designing and building a modulation transformer to handle the high audio modulating power required. High-level modulation has been used in AM transmitters up to at least 250 kW carrier power with a modulator output power requirement of 125 kW. By a unique design in which the positive terminal of the modulator plate supply is grounded, and autotransformer is used as the modulation transformer, with a significant reduction in size and cost.

CLASS B LINEAR RF AMPLIFIERS

The conventional means for achieving linear amplification of an AM signal is the class B rf amplifier circuit, often referred to simply as a *linear amplifier*. The plate efficiency, plate dissipation, and output power are highly dependent on the drive level. It is convenient, therefore, to define a *drive ratio* or normalized drive level k.

$$k = E_{pm}/E_{bb}$$

where E_{bb} is the dc plate supply voltage and E_{pm} is the peak ac plate signal voltage.

Class B amplifiers using transistors can approach the theoretical maximum collector efficiency of $\pi/4$, or 78.54 percent, as a consequence of the very low collector saturation voltage of transistors, which gives a correspondingly high value for K.

HIGH-EFFICIENCY POWER AMPLIFIERS

The plate efficiency at carrier level in a practical linear amplifier circuit is about 33 percent, while that of a high-level (plate) modulated stage is 65 to 80 percent. When the efficiency of the modulator is taken into account, the net efficiency of the high-level modulated stage is still higher than that of the linear amplifier, since the output power level of the modulator is at most one-third of the total output power of the modulated stage.

Because of the difficulty and expense involved in the design and manufacture of very large modulation transformers and chokes, several linear amplifier circuits having much greater efficiency than the class B amplifier while amplifying an AM waveform have been developed. Low-level modulation can be employed, and the need for the large, expensive modulator components is circumvented.

Such high-efficiency amplifier circuits include the Chireix outphasing modulated amplifier, the Dome high-efficiency modulated amplifier, the Doherty high-efficiency amplifier, and the Terman-Woodyard high-efficiency modulated amplifier.

INDUCTION HEATING CIRCUITS

Induction heating is achieved by placing a coil carrying alternating current adjacent to a metal workpiece so that the magnetic flux produced by the current in the coil induces a voltage in the workpiece, which produces the necessary current flow.

Power sources for induction heating, in addition to direct use of commercial power, include spark-gap converters, motor-generator sets, vacuum-tube oscillators, and inverters. Motor-generator sets generally provide outputs from 1 kW to more than 1 MW and from 1 to 10 kHz. Spark-gap converters are generally used for the frequency range from 20 to 400 kHz and provide output power levels up to 20 kW. Vacuum-tube oscillators operate at frequencies from 3 kHz to several MHz and provide output levels from less than 1 kW to hundreds of kilowatts. Inverters using mercury-arc tubes have been used up to about 3 kHz. Solid-state inverters operate at frequencies up to about 10 kHz and at power levels of several megawatts. These solid-state inverters generally employ thyristors (silicon controlled rectifiers) and are replacing motor-generator sets and mercury-arc inverters.

DIELECTRIC HEATING

Whereas induction heating is used to heat materials which are electrical conductors, dielectric heating is used to heat nonconductors or dielectric materials. The basic arrangement for a dielectric heating system is that of a capacitor in which the material to be heated forms the dielectric or insulator. The heat generated in the material is proportional to the loss factor, which is the product of the dielectric constant and the power factor. Because the power factor of most dielectric materials is quite low at low frequencies, the range of frequencies employed for dielectric heating is higher than for induction heating, extending from a few megahertz to a few gigahertz.

The power generated in a material is given by

$$P = 141AV^2 f \frac{K \cos\phi}{t} \times 10^{-6} \quad \text{(W)}$$

where V = voltage across material (V)
f = frequency of power source (MHz)
A = area of material (in^2)
K = dielectric constant
t = material thickness (in)
$\cos\phi$ = power factor of dielectric material

The voltage that can be applied to a particular material is limited by the insulation properties of the material at the required process temperature. The frequency that can be used is limited by voltage standing waves on the electrodes, which will be appreciable when the electrode dimensions are comparable with one-eighth wavelength (10 percent voltage variation).

TRANSISTORS IN HIGH-POWER AMPLIFIERS

Many high-power amplifier circuits can be implemented by using solid-state power devices. Bipolar transistors have been successfully applied in induction heaters, sonar transmitters, and broadcast transmitters. The sonar transmitters have employed class B, class C, and the so-called class D power amplifier circuits. In the class D circuit the active device is used as an on-off switch, and output power variations are achieved by pulse-width modulation or supply-voltage control. A tuned load or one incorporating a low-pass filter is used with the class D amplifier.

Power MOSFETs are advantageous compared with bipolar transistors in a number of applications. These include HF and VHF transmitters, high-speed power switching, and certain audio or low-frequency amplifiers.

The power MOSFET is a majority carrier device (contrast with a minority carrier device for the bipolar transistor). The input drive circuit requires current to supply the parasitic capacitances only. There is no minority carrier storage time or secondary breakdown. Switching time is usually much less than that of the bipolar transistor of the same die. The power MOSFET device uses a gate voltage-controlled circuit and requires very little current to maintain it in its OFF, ON, or an intermediate state. The ON resistance (r_{DS}) can vary from less than 0.5 Ω to several ohms depending on the device selected. There is a trade-off between high-breakdown drain-source voltage and low ON-resistance. For a given die size the ON-resistance varies as follows:

$$r_{DS} = K(V_{DS})^2$$

where K is a constant related to the die and V_{DS} is the maximum breakdown voltage between drain and source. A typical drain current (I_D)-drain-source voltage (V_{DS}) transfer characteristic curve of a TMOS power MOSFET is shown in Fig. 11.5.1. The ON-resistance r_{DS} is, of course, a function of the conduction state of the device and does have a threshold value depending on the gate voltage which controls the conduction (see Fig. 11.5.2). Also, if the design is dependent on the r_{DS} value, one must keep in mind a potential shortcoming which is its variation with temperature. Figure 11.5.3 shows this function with a Motorola MTM8N15. Temperature coefficients are provided as a function of I_D with a number of device data sheets. Switching speeds of this device are not influenced by temperature.

Considerations for Broadcast Transmitters. There are some advantages to using the power FET in this type of application through the VHF spectrum. The power FET offers stability in the drive circuit as well as its own transfer characteristics. With the bipolar transistor there is a dependent relationship between the collector current i_C and the current gain β. If the drive level is decreased, causing the i_C to decrease, the β will increase and can cause instability in an amplifier. The input impedance can also change as the drive level is changed. Both of these factors can become a stability design problem. The input and output impedances of the

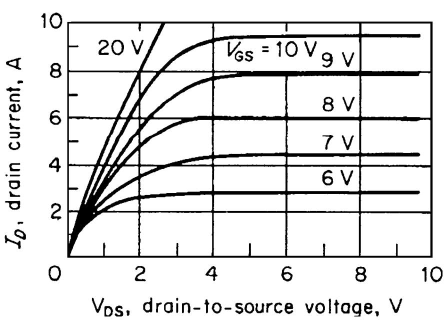

FIGURE 11.5.1 Typical on-region transfer characteristics for the MTP 7N05.06. *Copyright by Motorola, Inc. Used by permission.*

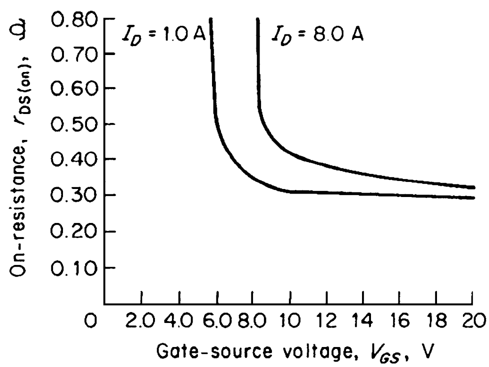

FIGURE 11.5.2 Variation of r_{DS} with V_{GS} and I_D for MTP8N15. *Copyrigth by Motorola, Inc. Used by permission.*

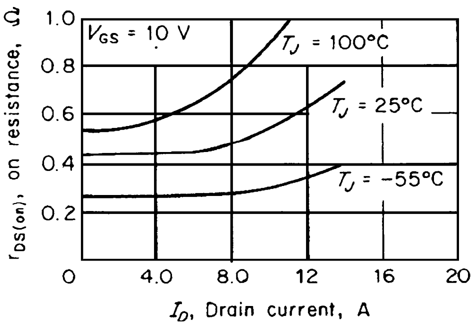

FIGURE 11.5.3 Variation of r_{DS} with drain current and temperature for MTM8N15. *Copyrigth by Motorola, Inc. Used by permission.*

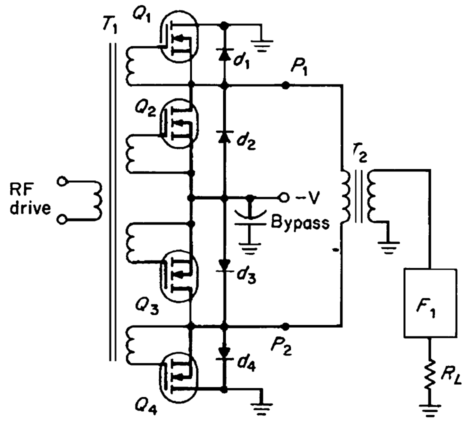

FIGURE 11.5.4 Power amplifier for Nautel broadcast transmitter.

device are reasonably independent of drive. The input impedance is somewhat higher in magnitude and more capacitive than bipolar devices, allowing simpler matching circuits to be used.

There are a number of approaches used in transmitter design. Which one to use depends on the number of modulation and carrier uses. Usually, a slightly positive (adjustable) bias is required on the gate unless strictly class C is needed. The amplifier design can be made to withstand high VSWR conditions in the output without damage. This is accomplished by selection of the device so that maximum rated drain-source voltage ($V_{(BR)DSS}$) is not exceeded. Likewise, the gate-to-source voltage (V_{GS}) cannot be exceeded. This is sometimes protected using a zener diode across the gate to source. Remember that using such devices tends to generate undesirable harmonics when the drive signal is clipped and a low-pass filter or equivalent is required in the output.

While power FET amplifiers can be operated in class A, B, AB, and C, it is of strong interest to consider class D for AM broadcast service. Power FETs can have a wide linear operating range and swinging them hard to an ON condition allows the efficiency to be quite high. Nautical Electronic Laboratories Limited of Nova Scotia has developed a very efficient AM transmitter using power FETs as switches (class D operation). Figure 11.5.4 shows the basic configuration of the final rf amplifier. A low-power rf drive signal at the carrier frequency is applied via $T2$ to bias FET pairs $Q1/Q3$ and commutated between input terminals of $T2$ as a square wave of reversing polarity at the carrier frequency. The resulting high-power signal at $T2$ is filtered by low-pass filter $F1$ to remove unwanted harmonics. The final rf amplifier is thus simply a device that converts from dc to rf. Efficiencies of greater than 90 percent are achievable.

The pulse width modulator also uses FETs in a switched mode to vary the negative supply to the rf power amplifier in sympathy with an audio modulating signal to produce high level modulation with a similar high efficiency. Nautical Electronic Laboratories has developed a 50-kW solid-state transmitter of this type with distortion typically less than 1.0 percent.

MOSFET AUDIO AMPLIFIERS AND SWITCHING APPLICATIONS

The power MOSFET offers a very linear transfer characteristic. This can be used effectively with the design of audio power amplifiers with proper gate biasing.

The gain characteristic is identified with the transconductance of the MOSFET. The voltage gain is as follows:

$$A_V = g_{fs} R_L$$

where g_{fs} is the transconductance and R_L is the equivalent load. The transconductance is defined as the ratio of the change in drain current relating to a change in gate voltage. This rating on a device is typically taken at half

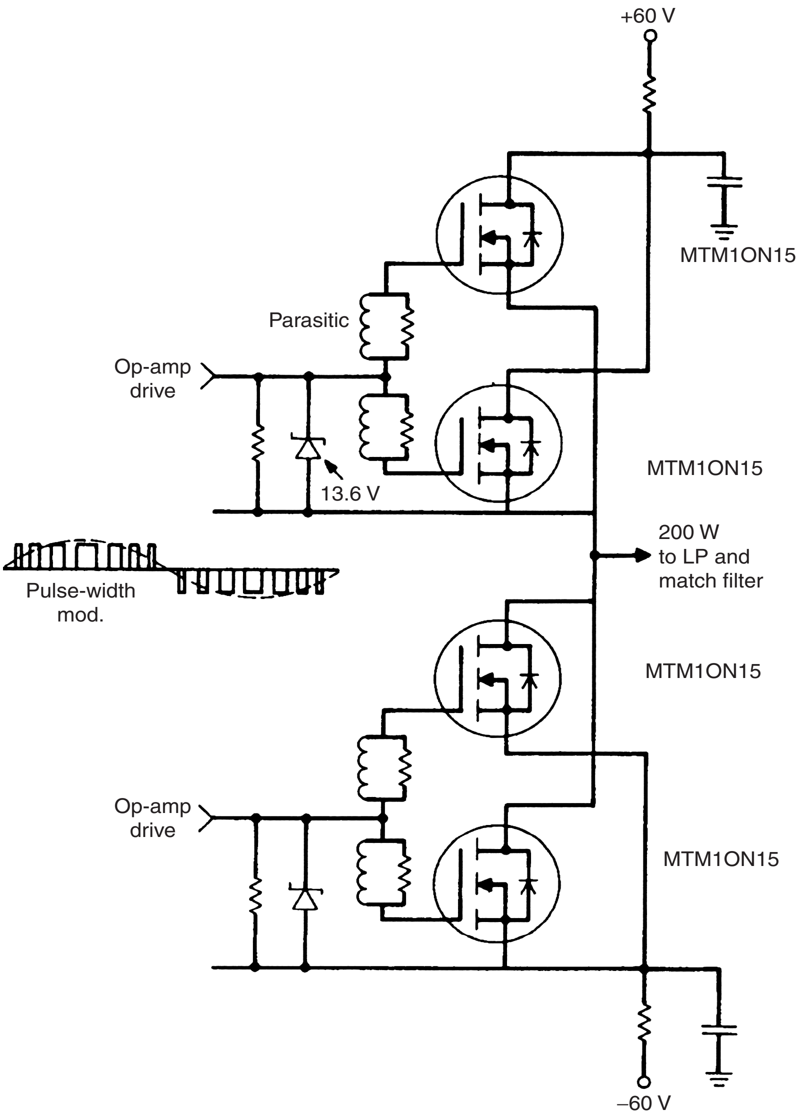

FIGURE 11.5.5 Class D audio amplifier using power MOSFET.

the rated continuous drain current at a V_{gs} of 15 V. The linear increase in g_{fs} with V_{gs} occurs in the square law region but levels off to a constant in the velocity-saturated region.

Considering the very high switching efficiency the power MOSFET has, it can be effectively used as a "class D" audio amplifier or one that is pulse-width modulated at the audio rate. A high-frequency carrier is used which is on the order of 6 to 10 times the highest audio-modulated frequency. The waveform is demodulated at the output for driving large speaker systems. Very high audio power amplifiers can be designed with high fidelity, small size, and high efficiency. Power FETs can be placed in parallel with few problems of current sharing. Figure 11.5.5 shows a simple version of this approach. With the high carrier frequency, coupling capacitors and supply decoupling become much less severe.