13 Tuned Power Amplifiers

Many applications do not require linear RF amplification and can therefore make use of the greater efficiency and simplicity offered by Class C tuned power amplifiers. Such applications include amplification of CW, FM, and AM (double-sideband, full-carrier) signals. The CW and FM signals have at most two possible amplitudes; the amplitude variation required for an AM signal is accomplished by variation of the supply voltage of the PA.

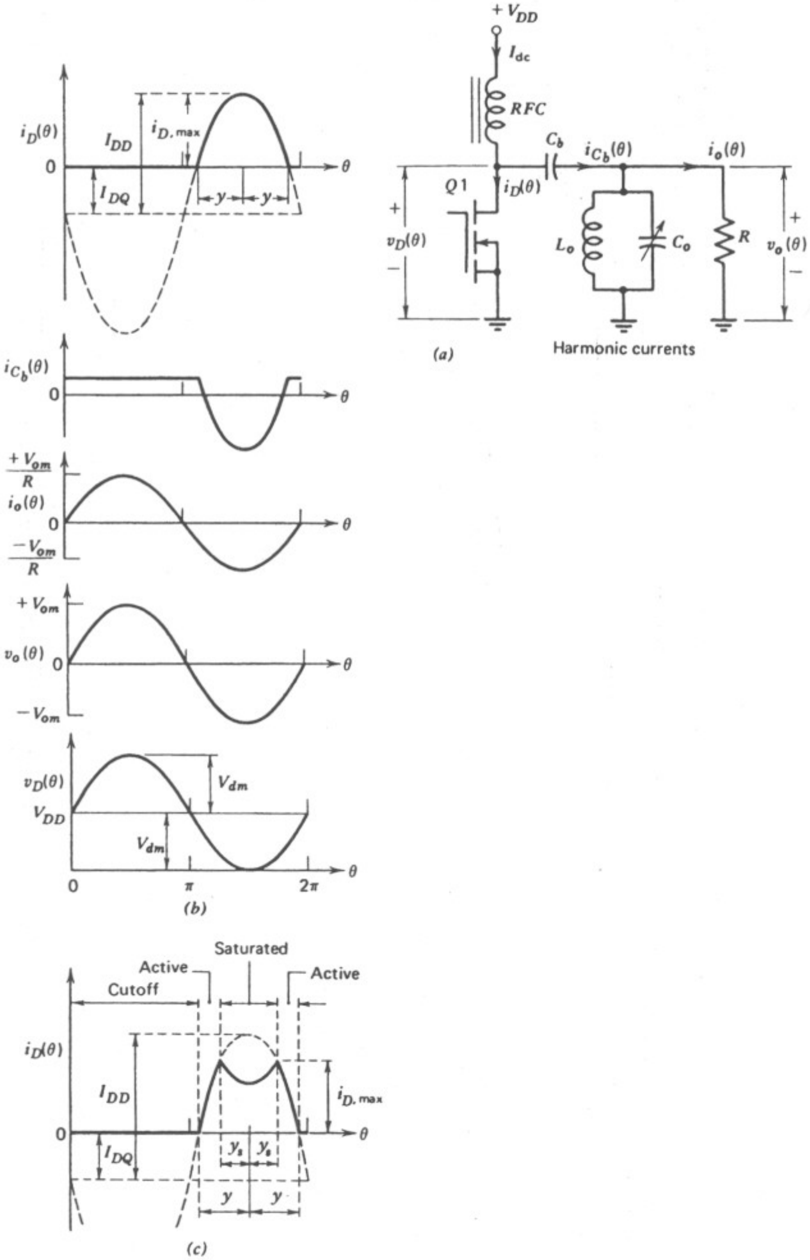
A tuned output circuit or filter is a necessary part of a Class C amplifier, rather than just a means of reducing harmonics in the output. In most applications where Class C is used, a narrow-band tuned circuit or matching network (rather than a broadband filter) is acceptable. The narrow-band tuned circuit or matching network can, of course, also be used with Class A and B linear PAs when broadband operation is not required.

It is important for the designer to be aware of the considerable difference between vacuum-tube and solid state versions of the Class C amplifier. The classical or true "Class C" PA that is widely used in vacuum-tube transmitters [1] uses its active device as a (possibly saturating) current source. The operation of its solid state equivalent is considerably more complex and is quite difficult to analyze analytically. It will be called "Class C mixed mode" to differentiate it from the classical "Class C" PA.

13-1 Current-Source Class C Amplifiers

The circuit topology (Fig. 13-1*a*) of the classical C power amplifier is the same as that of the Class A amplifier of Chapter 12. The active device is also driven

Fig. 13-1 Class C amplifier. (*a*) Circuit; (*b*) waveforms; and (*c*) drain current in a saturating Class C amplifier.



to act as a current source; however, the current waveform it produces is not (even in the absence of device nonlinearities) the sinusoidal current desired in the load. The current waveform may be a variety of shapes but is most often modeled as a biased sine wave of the form

$$i_D(\theta) = \begin{cases} I_{DQ} - I_{DD} \sin \theta, & I_{DQ} - I_{DD} \sin \theta \geq 0 \\ 0 \quad , & I_{DQ} - I_{DD} \sin \theta < 0 \end{cases} \tag{13-1}$$

This drain current waveform (Figure 13-1*b*) is thus a piece of a sinewave when the device is active or zero when the device is driven into cutoff. Note that current I_{DQ} (analogous to the quiescent current in a Class A or B PA) is negative in a Class C PA, while the current I_{DD} (resulting from drive) is positive.

The portion of an RF cycle that the device spends in its active region is called the conduction angle and is represented here by $2y$. The conduction angle is related to both the amount of bias current I_{DQ} and the amount of driven current I_{DD} by

$$y = \begin{cases} 0, \; I_{DD} + I_{DQ} < 0 & \text{(transistor cut off)} \\ \pi, \; I_{DQ} - I_{DD} > 0 & \text{(class A operation)} \\ \arccos\,(-I_{DQ}/I_{DD}), \text{ otherwise} & \text{(class B or C operation)} \end{cases} \tag{13-2}$$

Conversely, bias may be written as a function of a drive and conduction angle as

$$I_{DQ} = -I_{DD} \cos y \tag{13-3}$$

Note that these expressions include both Class A ($y = \pi$) and Class B ($y = \pi/2$), as well as Class C, which is defined by conduction for less than one-half of the RF cycle ($y < \pi/2$).

The supply current I_{dc} required with this drain current waveform is its dc component

$$I_{dc} = \frac{1}{2\pi} \int_0^{2\pi} i_D(\theta)\, d\theta = \frac{1}{\pi}(I_{DQ}y + I_{DD} \sin y) = \frac{I_{DD}}{\pi}(\sin y - y \cos y) \tag{13-4}$$

and the input power is then $P_i = V_{DD}I_{dc}$. Since the dc component of the drain current flows through the RF choke RFC, the ac component $i_{C_b}(\theta)$ flows through the blocking capacitor C_b and ultimately through the load or tuned circuit. The tuned circuit provides (ideally) a zero impedance path to ground for the harmonic currents contained in $i_{C_b}(\theta)$, thus (ideally) preventing the generation of harmonic voltages on the output. (Note that this requires the use of a parallel-tuned circuit, rather than a series-tuned circuit.) The parallel-tuned output circuit has, however, an infinite reactance to the fundamental frequency component of $i_{C_b}(\theta)$, thus forcing it entirely into the load R, where it generates output voltage $v_0(\theta) = V_{om} \sin \theta$.

The magnitude V_{om} of the output voltage is determined by multiplying the fundamental frequency component of $-i_D(\theta)$ by R, thus

$$V_{om} = -\frac{1}{\pi}\int_0^{2\pi} i_D(\theta)R \sin\theta \, d\theta = \frac{R}{2\pi}(4I_{DQ}\sin y + 2I_{DD}y + I_{DD}\sin 2y) \qquad (13\text{-}5)$$

$$= \frac{I_{DD}R}{2\pi}(2y - \sin 2y) \qquad (13\text{-}6)$$

The second step above is accomplished by using (13-2) to replace I_{DQ} in (13-5). The output power is then $P_o = V_{om}^2/2R$ and the efficiency is $\eta = P_o/P_i$. Note that the relationship between the driven current I_{DD} and output amplitude V_{om} is generally nonlinear (Fig. 13-3), since the conduction angle $2y$ is a function of the driven current I_{DD} (13-2). Exceptions occur when $y = \pi$ (Class A) and when $y = \pi/2$ (Class B). Single-ended Class B linear operation is thus possible if a parallel-tuned output circuit is provided.

The efficiency of a Class C amplifier, like that of a Class A or B amplifier, is generally highest at its peak output, that is, when the drain voltage swing $V_{dm} = V_{om} = V_{DD}$. Class C is most often used in applications where there is no variation of signal amplitude and where matching networks can be used. Consequently, it is usually possible to design a Class C amplifier to operate near its peak output and near its maximum efficiency.

The efficiency at peak output can be related directly to the conduction angle; this is especially useful when designing an amplifier to have a specified efficiency. Substitution of (13-2) into (13-4) gives I_{dc} and hence P_i in terms of I_{DD} and y. Fixing $V_{dm} = V_{DD}$ in (13-6) gives I_{DD} as a function of y. Since the output power is then $P_o = V_{DD}^2/2R$,

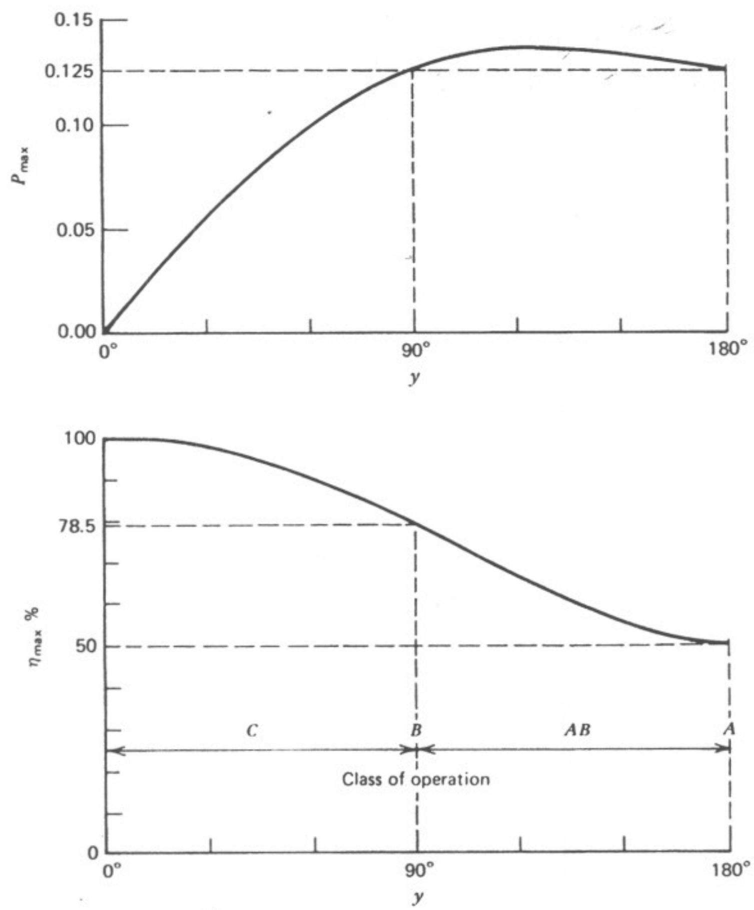
$$\eta_{\max} = \frac{2y - \sin 2y}{4(\sin y - y\cos y)} \qquad (13\text{-}7)$$

The power output capability (Section 12-1) can also be related to the conduction angle. Since $i_{D,\max} = I_{DQ} + I_{DD}$ and $v_{D,\max} = 2V_{DD}$,

$$P_{\max} = \frac{P_{o,\max}}{v_{D,\max}i_{D,\max}} = \frac{2y - \sin 2y}{8\pi(1-\cos y)} \qquad (13\text{-}8)$$

The variation of efficiency and power output capability with conduction angle are shown in Fig. 13-2. First, observe the familiar efficiencies of 50 and 78.5 percent for Class A and B operation, respectively. The efficiency of Class C operation can be increased toward 100 percent (in an ideal amplifier) by decreasing the conduction angle toward zero. The increase in efficiency can be attributed to drawing the drain current when the drain voltage is near its minimum. However, since this results in increasing the peak value of the drain current to maintain the same output, $P_{\max}$ decreases toward zero as the efficiency increases toward 100 percent. Designing a Class C amplifier there-

Fig. 13-2 Efficiency and power capabilities of Class C operation.



fore involves a trade-off between efficiency and design ratings, among other things. Note that with a single-ended (one transistor) PA for either Class A or B operation, $P_{max} = \frac{1}{8}$; this is consistent with $P_{max} = \frac{1}{4}$ for the push-pull Class B amplifier of Chapter 12, which has two transistors.

As mentioned previously, the drain voltage waveform need not be a piece of a sinewave. In fact, it usually differs somewhat from the idealized model used here. Several other models [2–5] have been used, including exponential, quartic, and rectangular shapes, as well as shapes derived from vacuum-tube characteristic curves. Results are generally similar [2]. An interesting aspect of a rectangular drain waveform is that the amplitude transfer characteristic is linear, regardless of the conduction angle [4].

Practical considerations prevent the attainment of the efficiency and power output indicated by the foregoing idealized equations. The effects of saturation voltage can be determined by using $V_{eff} = V_{CC} - V_{sat}$ in place of V_{CC} in all computations except for input power, just as for a Class B PA. Because of saturation resistance R_{on}, an FET enters saturation (Fig. 12-2) during a portion of the RF cycle if the minimum drain voltage $V_{DD} - V_{dm}$ is equal to or less than $I_{Dm}R_{on} = (I_{DQ} - I_{DD})R_{on}$; note that this differs from the form given in Section 12-3 for Class B PAs. The effects of reactance in the load of a Class C PA are similar to those in a Class B PA and are treated in the same way (Section 12-3).

Example 13-1.1. Design a Class C PA to deliver 25 W to a 50-ohm load with an efficiency of 85 percent (ignoring saturation effects). Operation will be at 50 MHz and the power source will be +12 V: First, $V_{DD} = 12$ V and $P_o = 25$ W imply a load of $R = 12^2/((12)(25)) = 2.88$ ohms, which should be obtained by using a pi-matching network with a Q of 5 or more. Iterative solution of (13-7) aided by Fig. 13-2 (or inspection of Appendix 14-1) gives $y = 73.5°$ (1.282 rad) for $\eta_{max} = 85$ percent. Inserting y and $V_{om} = 12$ into (13-6) gives $I_{DD} = 12.97$ A; (13-2) then gives $I_{DQ} = -3.70$ A. From these, the maximum device current is $i_{D,max} = 12.97 - 3.70 = 9.27$ A; the maximum device voltage is $2 \times 12 = 24$ V. The bias and driven currents (I_{DQ} and I_{DD}) are obtained by application of analogous voltages to the gate.

13-2 Saturating Class C Amplifiers

Class C power amplifiers are typically driven hard enough to cause the transistors to enter saturation during a portion of each RF cycle [6, 7]. Saturated operation is advantageous because it produces an RF voltage source whose amplitude depends primarily upon the drain supply voltage and is largely insensitive to variations in the amplitude of the driving signal. This property enables the generation of amplitude-modulated signals through variation of the drain supply voltage. Additionally, some increases in the output power and efficiency are possible.

The parallel-tuned output circuit is assumed to maintain sinusoidal output and drain voltages at all times, as in a nonsaturating Class C PA., While saturated, an FET is conveniently modeled as a constant resistance R_{on} (Fig. 12-2). BJTs must be modeled as having both a saturation resistance R_{on} and a saturation voltage V_{sat}. (The subsequent discussions show only R_{on}; saturation voltage effects are included by using $V_{eff} = V_{CC} - V_{sat}$ in place of V_{CC} everywhere except in the calculation of P_i). The collector current waveform (Fig.