The ABC's of PA's

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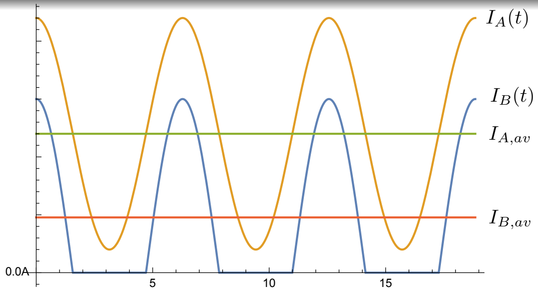
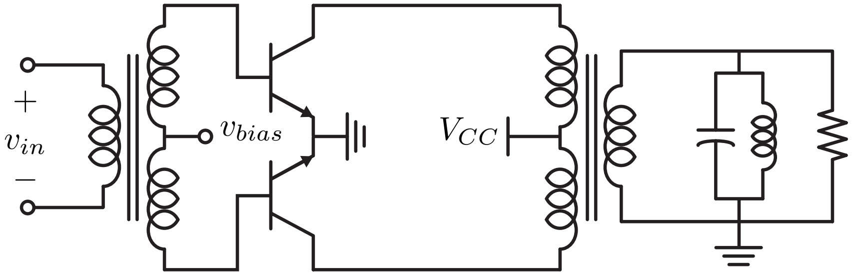
PA Classes



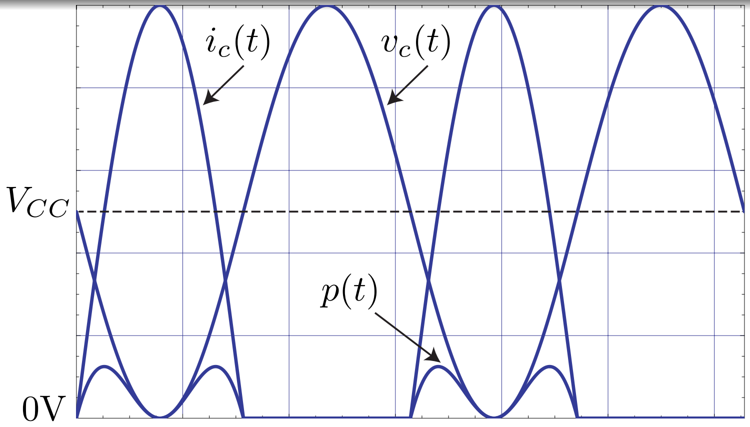
- Up to now we have been designing PA's as linear amplifiers, also known as Class A. We bias the transistors with enough DC current to support the load. In practice we may bias it higher the the load in order to reduce the amount of distortion, which is application dependent.
- While counterintiuitive, it's possible to actually bias the transistor so that it's on only half of the time, and yet preserve the linearity of the amplifier. This is known as a Class B amplifier, which a conduction angle of 180°, in contrast to a Class A amplifier that has a conduction angle of 360°. Lower than 180° is known as Class C.

Class B PA's



- The above circuit utilizes two transistors. Each device only delivers a half sinusoid pulse and the full sinusoid is recovered by phase inversion through the transformer.
- The base and collector bias voltages come from the transformer center tap. The base (or gate) is biased at the edge of conduction (threshold).

Class B Waveforms



- Since the voltage at the load is ideally a perfect sinusoid, the voltage on the collectors is likewise sinusoidal.
- The power dissipated by each transistor is thus the product of a sine and a half sine as shown above.

Class B Efficiency

- The average current drawn by each transistor is given by

$$I_Q = \frac{1}{T}\int_0^T i_c(t)dt = \frac{I_p}{T}\int_0^{T/2} \sin \omega t dt = \frac{I_p}{2\pi}\int_0^{\pi} \sin \theta d\theta = \frac{I_p}{\pi}$$

- Where I_p is the peak voltage drawn from the supply.
- The peak current drawn from the supply is just the load current swing reflected to the collector, $I_p = i_o \times n$.

$$\eta = \frac{1}{2}\left(\frac{I_p}{2I_Q}\right)\left(\frac{v_o}{V_{CC}}\right)$$

- Note that the total DC current draw is twice I_Q since both devices draw current from the supply.

Class B Efficiency (cont)

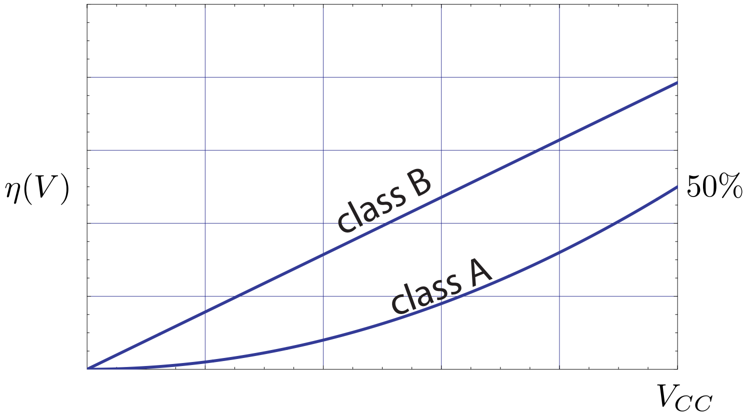
- Since the collector voltage swing can be as large as V_{CC} (similar to an inductively loaded Class A), the efficiency is bounded by

$$\eta \leq \frac{1}{2}\left(\frac{I_p}{2I_Q}\right) = \frac{1}{4}\left(\frac{I_p}{I_Q}\right)$$

$$\eta \leq \frac{\pi}{4} \approx 78\%$$

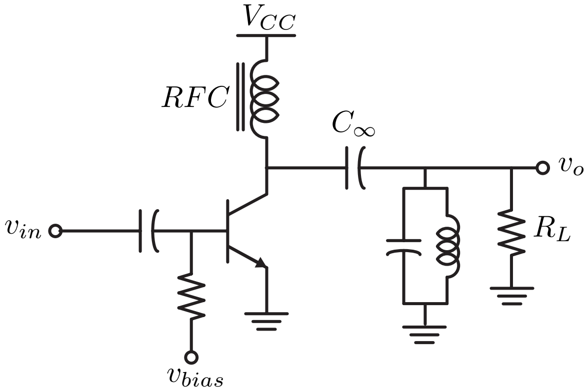
- This is a big improvement over the peak efficiency of Class A.
- Note that the average current naturally scales with output power, and so efficiency drops more gracefully as we back-off from peak power.

Efficiency versus Back-Off



- The efficiency drops linearly as we back-off from the peak output voltage
- where v_c is the collector voltage swing, which is just n times smaller than the load voltage, $v_c = v_o/n$.

Tuned Class B



- A tuned Class B amplifier works with a single devices by sending half sinusoid current pulses to the load. The device is biased at the edge of conduction.
- The load voltage is sinusoidal because a high Q RLC tank shunts harmonics to ground.

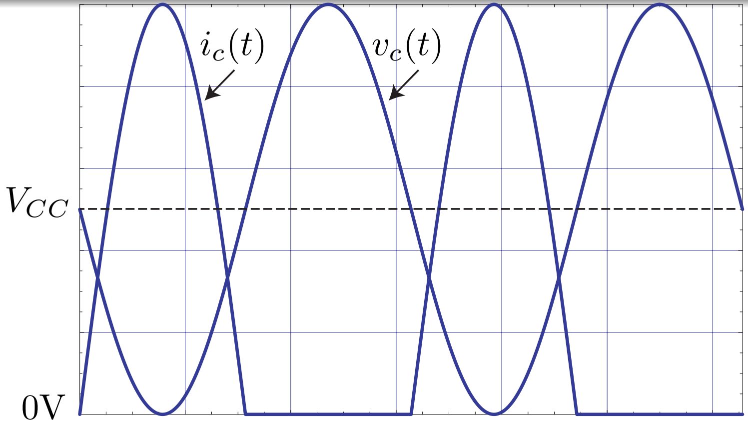
Class B Tank

- In a single transistor version, the "minus" pulse is in fact delivered by the RLC tank. The Q factor of the tank needs to be large enough to do this. This is analogous to pushing someone on a swing. You only need to push in one direction, and the reactive energy stored will swing the person back in the reverse direction.
- The average current drawn from the supply is the same as before, $I_Q = I_p/\pi$. The harmonic current delivered to the load is given by Fourier analysis of the half pulse

$$I_{\omega_1} = \frac{2}{2\pi} I_p \int_0^{\pi} \sin\theta \sin\theta d\theta = \frac{1}{\pi} I_p \int_0^{\pi} \frac{1-\cos 2\theta}{2} d\theta$$

$$= \frac{1}{\pi}\frac{\pi}{2} I_p = \frac{I_p}{2}$$

Class B Waveforms



- We see that the transistor is cut-off when the collector voltage swings above V_{CC}. Thus, the power dissipated during this first half cycle is zero.
- During the second cycle, the peak current occurs when the collector voltage reaches zero.

Class B Efficiency (again)

- The efficiency is therefore the same

$$\eta = \frac{1}{2}\frac{I_{\omega_1}}{I_Q}\frac{v_c}{V_{CC}} \leq \frac{1}{2}\frac{\pi}{2} = \frac{\pi}{4}$$

- The DC power drawn from the supply is proportional to the output voltage

$$P_{dc} = I_Q V_{CC} = \frac{V_{CC} I_p}{\pi}$$

$$I_p = \frac{v_c}{R_{opt}} = \frac{n v_o}{R_{opt}}$$

- The power loss in the transistor is given by

$$p_t(t) = \frac{1}{2\pi}\int_0^{\pi} I_p \sin\theta (V_{CC} - v_c \sin\theta) d\theta$$

Transistor Power Loss

- Integrating the above expression

$$p_t(t) = \frac{V_{CC} I_p}{2\pi} \left(-\cos\theta \right|_0^{\pi} - \frac{v_c}{I_p} 2\pi$$

$$= \frac{1}{2\pi} \left(2 V_{CC} I_p - \frac{v_c I_p}{2} \pi \right)$$

$$= \frac{I_p}{\pi} V_{CC} - \frac{v_c I_p}{4}$$

$$= I_Q \cdot V_{CC} - \frac{v_c I_{\omega_1}}{2}$$

$$= P_{dc} - P_L$$

Class B Power Capacity

- Recall the definition for PC

$$PC = \frac{P_{out}}{V_{max} I_{max}}$$

$$V_{max} = 2V_{CC}$$

$$I_{max} = I_{out}$$

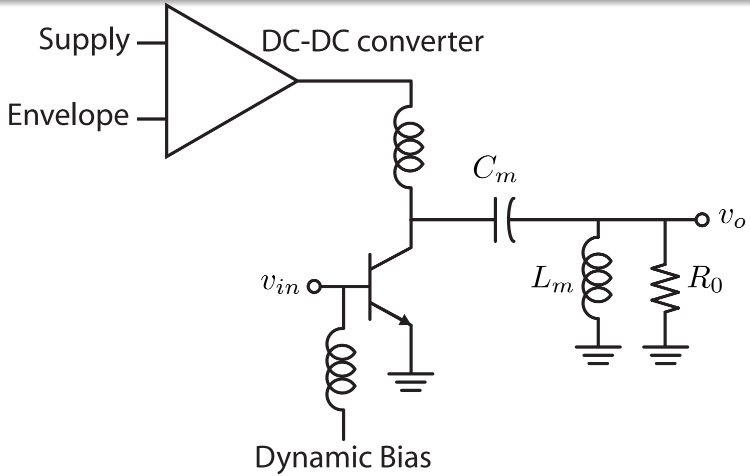
- Note that the output power is related to the fundamental coefficient of a half sine wave, or 1/2 the peak

$$P_{out} = \frac{1}{2} V_{CC} \frac{I_{out}}{2}$$

$$PC = \frac{\frac{1}{2} V_{CC} \frac{I_{out}}{2}}{2V_{CC} I_{out}} = 0.125$$

- Same as Class A

Dynamic PA



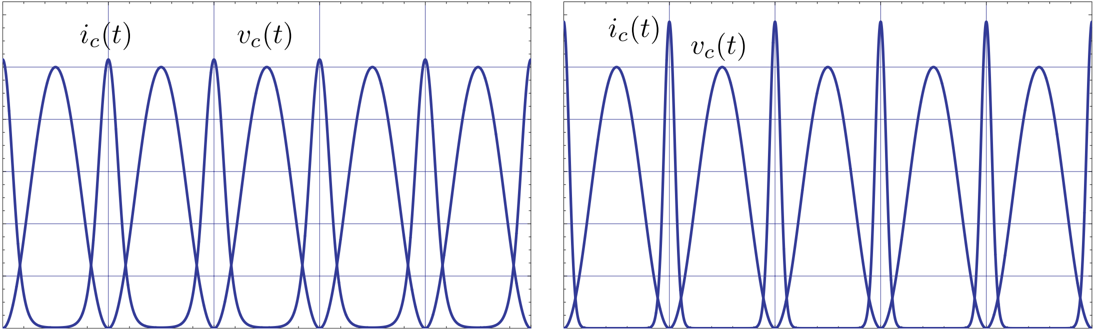
- Envelope tracking supply and dynamic class-A
- Efficiency always close to peak efficiency of amplifier (say 30%) regardless of PAR
- Need a very fast DC-DC converter

Class C PA's

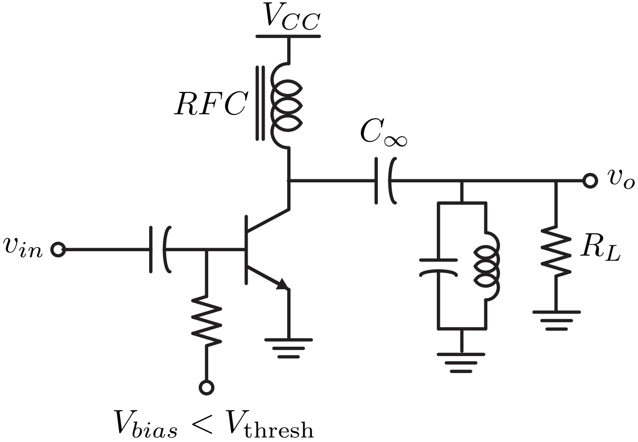
Conduction Angle

- Often amplifiers are characterized by their conduction angle, or the amount of time the collector current flows during a cycle.
- Class A amplifiers have 360° conduction angle, since the DC current is always flowing through the device.
- Class B amplifiers, though, have 180° conduction angle, since they conduct half sinusoidal pulses.
- In practice most Class B amplifiers are implemented as Class AB amplifiers, as a trickle current is allowed to flow through the main device to avoid cutting off the device during the amplifier operation.

Reducing the Conduction Angle

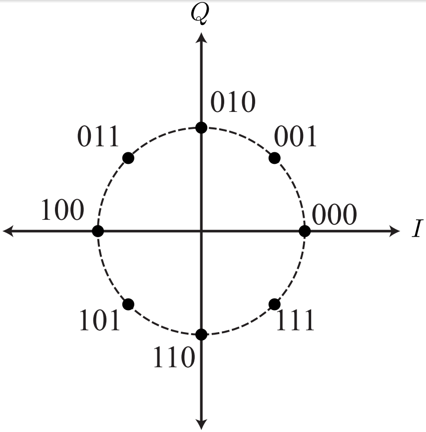


- The most optimal waveform is shown above, where a current pulse is delivered to the load during the collector voltage minimum (ideally zero)
- As the pulse is made sharper and sharper, the efficiency improves. To deliver the same power, though, the pulse must be taller and taller as it's made more narrow. In fact, in the limit the current spike approaches a delta function.



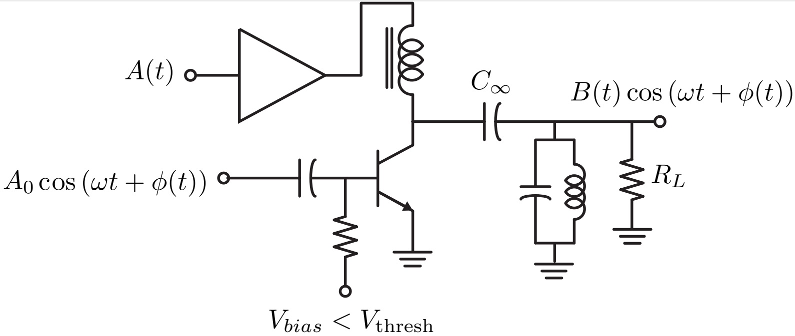
- Class C amplifiers are a wide family of amplifiers with conduction angle less than 180°. One way to achieve this is to bias a transistor below threshold and allow the input voltage to turn on the device for a small fraction of the cycle.

Class C Linearity



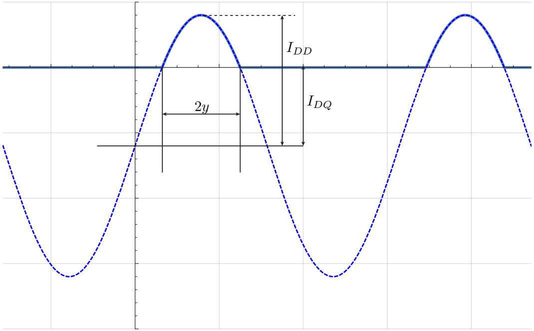
$$I^2 + Q^2 = A^2$$

- The Class C amplifier is very non-linear, and it is only appropriate for applications where the modulation is constant envelope. For instance, FM uses a constant amplitude carrier and only modulates the frequency to convey information. Likewise, any digital modulation scheme with a constellation on a circle is constant envelope



- While the amplifier is a non-linear function of the input amplitude, the Class C amplifier can be made to act fairly linearly to the collector voltage.
- By driving the amplifier into "saturation" in each cycle, e.g. with a large enough swing to rail the supplies, then the output power is related to the voltage supply. Collector modulation then uses the power supply to introduce amplitude modulation into the carrier.

Class C Approximate Analysis



- Assume current pulses are sine wave tips, conduction angle is $2y$

$$I_{DD} \cos y = I_{DQ} \qquad y = \cos^{-1}\left(\frac{I_{DQ}}{I_{DD}}\right)$$

$$i_D(\theta) = \begin{cases} -I_{DQ} + I_{DD}\sin\theta & I_{DD}\cos\theta \geq I_{DQ} \\ 0 & \text{otherwise} \end{cases}$$

Class C Average Current

- To make the integral easy to calculate, change variables to the range of y to 0.
- I_{DC} from supply:

$$I_{DC} = \frac{1}{2\pi} \int_0^{2\pi} i_D(\theta) d\theta = \frac{1}{\pi} \int_0^{y} (I_{DD} \cos\theta' - I_{DQ}) d\theta'$$

$$I_{DC} = \frac{1}{\pi}(I_{DD} \sin y - I_{DQ} y)$$

$$I_{DC} = \frac{I_{DD}}{\pi}(\sin y - y \cos y)$$

Class C Analysis (cont)

- Output voltage is: $V_{OM} = \text{Fund}\{-i_D(\theta)R_L\}$
- Since i_D is an odd function, the Fourier series will only yield sine terms

$$V_{OM} = \frac{-2R_L}{2\pi}\int_0^{2\pi} i_D(\theta)\sin\theta d\theta = \frac{2R_L}{\pi}\int_0^{y}(I_{DD}\cos\theta - I_{DQ})\cos\theta d\theta$$

$$V_{OM} = \frac{2R_L}{\pi}(\frac{I_{DD}y}{2} + \frac{I_{DD}\sin 2y}{4} - I_{DQ}\sin y)$$

$$V_{OM} = \frac{I_{DD}R_L}{2\pi}(2y - \sin 2y)$$

Note: $I_{DQ}\sin y = I_{DD}\cos y \sin y = \frac{I_{DD}}{2}\sin 2y$

- DC power from prev page: $P_{DC} = I_{DC}V_{CC} = \frac{I_{DD}V_{CC}}{\pi}(\sin y \cos y)$
- Assuming that max swing $\sim V_{CC}$:

$$V_{OM} \approx V_{CC} = \frac{I_{DD}R_L}{2\pi}(2y - \sin 2y)$$

Class C Efficiency

$$P_{DC} \approx \frac{2V_{CC}^2}{R_L}\frac{\sin y - y\cos y}{2y - \sin 2y}$$

- Power to load (assuming V_{CC} swing): $P_L = \frac{V_{CC}^2}{2R_L}$
- Ideal Efficiency:

$$\eta = \frac{P_L}{P_{DC}} = \frac{1}{4}\frac{2y - \sin 2y}{\sin y - y\cos y}$$

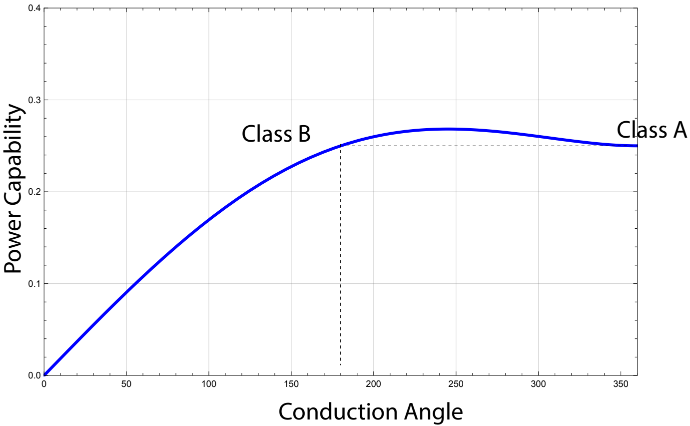
$$\lim_{y\to 0}\eta(y) = 100\% \quad \text{(ideal class C)}$$

$$\eta(\pi) = 50\% \quad \text{(tuned-circuit Class A)}$$

$$\eta(\pi/2) = 78.5\% \quad \text{(single-ended Class B)}$$

- For small conduction angle current pulses approach delta-function.
- Many practical issues make Class C difficult to design.

Power Capacity of Class C



$$V_{drain,max} = 2V_{CC}$$

$$I_{D,max} = I_{DD} - I_{DQ}$$

$$= I_{DD}(1 - \cos y)$$

$$PC = \frac{P_o}{2V_{CC} I_{DD}(1 - \cos y)}$$

$$= \frac{1}{4\pi}\frac{2y - \sin 2y}{1 - \cos y}$$

- The power capacity of Class C is low at low conduction angles. Peak is Class AB.