For class A operation, M1 is biased to remain in the saturation region.
- For this analysis, we assume the operation is linear, and it is an ideal transconductor.
- Like the small-signal amplifiers we are used to, but here the signal current is a substantial fraction of the dc current.

Let's assume that the drain current in M1 is: \( I_D = I_{DC} + i_{DS} \sin(\omega t) \)
- Since the BFL current is constant, \( V_{DS} = -i_{DS} \sin(\omega t) R_L \)
  (we assume M1 has infinite O/P resistance)
- Drain voltage of M1 is dc level + signal: \( V_D = V_{DD} - i_{DS} \sin(\omega t) R_L \)

Plot waveforms: \( V_D \)

\[ \text{Plot waveforms:} \quad V_D \]

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Calculate efficiency:
- Power to load is \( P_L = \frac{i_{DS}^2 R}{2} \)
- Power from supply is \( P_S = V_{DD} I_{DC} \)

\[ \eta = \frac{i_{DS}^2 R}{2 \cdot V_{DD} I_{DC}} \]

- Efficiency increases for higher \( i_{DS} \), maximum value \( \eta \) can have without M1 entering cut-off is \( \eta = 1 \)
- Efficiency also improves for decreasing \( i_{DS} R \).

\[ \text{Maximum efficiency is } \eta = \frac{V_{DD} I_{DC}}{2 \cdot V_{DD} I_{DC}} = 50\% \]

- Now if we were to use conjugate match for more power transfer, this would be halved again to 25%.
- This represents a maximum attainable value; in reality, it will be needing to maintain some finite \( V_{DS} \) to keep the transistor in saturation, so efficiencies will be more like 30-40%.

- We would like to do better than this, let's examine what happens when we loosen the restriction of keeping the transistor in saturation.
For a class B amplifier, the transistor is biased to be on for only half of each cycle.

The drain current in RL is now: \( i_D = i_{in} \sin \omega t \), for \( i_{in} > 0 \)

Plot waveforms:

- Clearly, this drain current will produce significant non-linearities in the output signal, as plotting \( i_D \) we have assumed there are filtered out and only the fundamental remains.

- We have reduced the time for which \( V_D \) is positive, so we expect the transistor will waste less power.

To find output voltage, first find the component of drain current and multiply by the load resistor:

\[
\text{fund} = \frac{2}{T} \int_0^{T/2} i_{in} \sin(\omega t) \sin(\omega t) \, dt = \frac{i_{in}}{2}
\]

\( V_{out} = i_{in} R \cdot \sin \omega t \)

- We know the max. amplitude for \( V_{out} = V_{DD} \), so \( V_{DD} = \frac{i_{in} R}{2} \)

- Now, for drain efficiency, the power to the load is:

\[
P_L = \frac{V_{DD}^2}{2R}
\]

- We need to integrate to find the power drawn from the supply:

\[
\overline{i_D} = \frac{1}{T} \int_0^{T/2} 2V_{DD} \sin \omega t \, dt = \frac{2 \cdot V_{DD}}{\pi R}
\]

\( P_s = \frac{2V_{DD}^2}{\pi R} \)

- Efficiency: \( \eta = \frac{P_L}{P_s} = \frac{\pi}{4} \approx 78.5 \% \)

- So, the efficiency is significantly better than for class A, at the expense of more output distortion required due to the increased non-linearity.
Definition: Conduction Angle - the percentage of the cycle (in degrees) for which the drive transistor M1 is turned on.

- For a class A amplifier, the conduction angle is 360° (full cycle).
- For the class B amplifier, the conduction angle is 180° (half cycle).

→ Can we obtain a further gain in efficiency by reducing the conduction angle even further?

3. Class C

→ For a class C amplifier, the conduction angle is less than 180°.

- We assume that sufficient filtering results in only the fundamental term appearing in the output voltage, so the Vcc plot stays the same as for class A or B.

\[ \text{Plot Io: } \quad I_{o} = \frac{V_{cc}}{R_{L}} \]

→ So, we have reduced the duration for which io is positive, so we expect a further increase in efficiency.

- In a similar manner to what was done for the class B (but easier since we don't have clean 1/2 cycles to deal with), we can compute the efficiency.

→ Skipping the proof details, the result is:

\[ \eta = \frac{2(\theta - \sin(2\theta))}{4(\sin^2 \theta - \theta \cos \theta)} \]

- So, as \( \theta \to 0 \), \( \eta \to 100\% \) (not obvious, need to use l'Hopital's rule to show this)

- Problem: as efficiency tends towards 100\%, power delivered to the load tends towards 0.

- 100\% efficiency cannot be realized in practice.

4. Class AB

→ This is just an amplifier biased to conduct between 100\% (class A) and 50\% (class B) of the time.

To look at the amplifier in terms of conduction angle:

\[ \begin{align*}
0° & \quad 180° & \quad 360° \\
\uparrow & \quad \uparrow & \quad \uparrow \\
C & \quad B & \quad A \\
& \quad AB
\end{align*} \]
In the practical amplifiers we have seen so far, the efficiency is limited since there exist times when both $V_{ds}$ and $V_{gs}$ are non-zero.

- If the transistor acted as a switch ($V_{ds} = 0$ when switch is on and $V_{gs} = 0$ when switch is off) we could get 100% efficiency while delivering power.

**Class D**

- This amplifier exploits this fact:

**Operation**
- $T_1$ ensures only one transistor is on for a given time.
- Transistors are driven hard enough to act as switches.

- Transistors alternately drive $T_2$ nodes to 0V, so the other goes to $2V_{DD}$.
- Impedance seen through $T_2$ is high at all frequencies but the fundamental so only this current flows in the transformer (both primary and secondary coils).

Now, since one of $V_{ds}$ or $V_{gs}$ for each transistor is always 0, we can get 100% efficiency while delivering power to the load.

- In practice, finite switching times will lead to power dissipation since amplifiers are most effective when the transistors are well below their $f_t$ values.

The book describes 2 more topologies, class E and F (several variants), which use more complex resonant loads to resolve the problem of power dissipation due to finite transistor switching times.
Power Amplifier Modulation

- Depending on the type of modulation, we may desire the output signal amplitude of the PA to be linearly proportional to the input.
  - e.g., ASK, Q-PSK, QAM
  - Most modern systems use complex modulation that requires this.

- This is satisfied for class A & B amplifiers since Vout is proportional to Vdc if the transistor is linearly conductive.

- For other amplifiers, we need another way of achieving this.

- Drain modulation: supply amplitude modulation by varying the effective power supply voltage

- Here, M2 acts as a class A amplifier, varying the effective Vdd seen by the BFL if the drive transistor M1.

- So now we can achieve an output amplitude that is proportional to the input, but we still need to be concerned with linearity for out of band emissions.

- This is a major issue for PAs, and there are many linearization techniques for dealing with this problem.
  - We will mention a couple of them here:

- Pre-distortion: can be done at baseband in the digital domain.

- This is a powerful technique in analog design in general (it is how a basic current mirror works).

- Envelope Elimination & Restoration:

- many more in the textbook...