Class E Amplifier

Clever resonant load is constructed so that $V(t)=0$ when the switch closes!! This avoids $1/2CV^2f$ loss.

- Voltage across switch is brought to zero when switch closes
- $dV/dt$ is also zero when switch closes. This makes operation relatively insensitive to rise time of input.
Class E Amplifier

Clever resonant load is constructed so that $V(t)=0$ when the switch closes!! This avoids $1/2Cv^2f$ loss.

V=0
dV/dt=0

Voltage across switch is brought to zero when switch closes

$dV/dt$ is also zero when switch closes. This makes operation relatively insensitive to rise time of input.

This is essential
If device does not have enough Cds then you must add this
Class E Amplifier

- Load current is sinusoidal (just \( f_0 \)) due to filter
- Switch and capacitor provide current during different phases

\[
\begin{align*}
\text{Load current} & = \text{sinusoidal (just } f_0 \text{) due to filter} \\
\text{Switch and capacitor} & = \text{provide current during different phases}
\end{align*}
\]

\[
\begin{align*}
\text{Capacitor current} & = \text{dc only} \\
\text{Output current} & = \text{ac only} \\
\text{At } f_0 & = \text{Id is zero for half the time} \\
\text{Ic has to provide current to load} & \text{ when switch is off}
\end{align*}
\]
Load current is sinusoidal (just fo) due to filter

Switch and capacitor provide current during different phases

\[ I_{\text{out}} \text{ is ac only} \]

\[ I_{\text{o}} \text{ is dc only} \]

At fo

Capacitor current
Class E Amplifier

V=0 and dV/dt =0 are achieved by carefully tuning Lextra of resonator, Cp and RL in relation operating frequency (and duty cycle of switch)

Filter that passes fo only; mistuned to look inductive

Capacitor C is often just the output capacitance of the switch

Capacitor current
Simple Analysis of Class E Amplifier

This is done in time domain!

Perfect choke: $I_o = \text{constant}$

Perfect filter: $I_g = -I_L \sin(\omega t + \phi)$

Calculate $V_c(t)$ when switch is open

$$C \frac{dV_c}{dt} = I_o + I_L \sin(\omega t + \phi)$$

$$V_c(t) = \frac{I_o t}{C} - \frac{I_L}{\omega C} \left[ \cos(\omega t + \phi) - \cos\phi \right]$$

Require $V_c = 0$ at $\omega t = \pi$:

$$\frac{I_o}{\omega C} - \frac{I_L}{\omega C} (-2 \cos\phi) = 0$$

$$I_o = -2 I_L \cos\phi$$

Require $\frac{dV_c}{dt} = 0$ at $\omega t = \pi$:

$$I_o + I_L \sin(\pi + \phi) = 0$$

$$I_o = I_L \sin\phi$$

$$\tan \phi = \frac{\sin\phi}{\cos\phi}$$
Class E Analysis (more)

\[ V_c(t) = \frac{I_0 t}{C} - \frac{L I}{\omega C} \left[ \cos(\omega t + \phi) - \cos \phi \right] \]

\[ I_0 + I_L \sin(\pi + \phi) = 0 \]
\[ I_0 = I_L \sin \phi \]

\[ \tan \phi = \frac{\sin \phi}{\cos \phi} \]

\[ \phi = -32.5^\circ \]
\[ I_L = 1.862 \, I_0 \quad I_{\text{peak}} = 2.862 \, I_0 \]

\[ V_{cc} : \text{dc component of } V_c(t) = \frac{I_0}{\pi} \frac{1}{\omega C} \]

\[ V_L : \text{Fourier component at } \omega \text{ of } V_c(t) = \frac{0.52 \, I_0}{\omega C} \]

\[ Z_L \rightarrow Z_L = \frac{0.18}{\omega C} + j \frac{0.21}{\omega C} \]

\[ P_{\text{out}}(\omega) = \frac{1}{2} R_L I_L^2 \]
Class E Design Equations

\[
Z_{out} = \frac{0.28015}{\omega C} e^{j49.0524^\circ}
\]

\[
f_{opt} = \frac{I_{max}}{56.5CV_d}
\]

\[
\eta_d = \frac{1 + (\pi/2 + \omega CR)^2}{1 + \pi^2/4 (1 + \pi \omega CR)^2}
\]

(\text{for fundamental, after } C_P)

\[
\frac{a_{18}}{\omega C} + j\frac{0.21}{\omega C}
\]

\text{Drain efficiency when on-resistance } R \text{ is included}
Class E Features

- Efficiency is 100% (ideally) No dissipation in transistor
- If frequency changes, then Vce does not quite go to 0 at switching instant => non-zero power dissipation due to $C\Delta V^2$
- Amplitude of output depends on Vcc (not on input amplitude)
- $P_{out} \ at\ f_o = 0.78 \times 1/8 \times V_{max} \ I_{max}$ (lower than for Class A)
Nathan Sokal
Another Description of Class E

\[ Z_{L}(f) = R_L + jX_L \]
with \( X_L = +0.72 \) \( R_L \)

\[ Z_{L}(2f) = -jX_2 \]
with \( X_2 = 1.78 \) \( R_L \)

\[ Z_{L}(3f) = -jX_3 \]
with \( X_3 = 1.19 \) \( R_L \)
Class E: Additional Implementations

Use transmission lines instead of lumped elements

\[ Z = \text{infinite at all harmonics} \]

Inductive at \( f_0 \)
Class E with transmission lines: approximation

Two-harmonic collector voltage approximation

Optimum impedance at fundamental seen by device:

\[ Z_{\text{net1}} = R \left( 1 + j \tan 49.052^\circ \right) \]

- Electrical lengths of transmission lines \( l_1 \) and \( l_2 \) should be of 45° to provide open circuit seen by device at second harmonic.

- Their characteristic impedances are chosen to provide optimum inductive impedance seen by device at fundamental.

- For three harmonic approximation, additional open circuit transmission line stub with 90-degree electrical length at third harmonic is required (1.5 GHz, 1.5 W, 90%).
Another Style of Design for Class E

This is not an ideal choke, it is carefully tuned to resonate with $C$

This resonator is tuned to $f_0$ (not mistuned as in classical Class E)

Approach of Grebennikov and Jaeger
Grebbenikov Design
Implemented with Transmission Lines
for LDMOS Switch
Grebbenikov Design
Implemented with Transmission Lines
And HBTs for handsets
World Record 2.0 GHz High Efficiency GaN Amplifier

- Class E Hybrid amplifier
- $V_d = 30$ volts
- $50\Omega$ input/output
- $10\ W P_{\text{out}}, 88\%$ Drain Efficiency!
- $1.9 \rightarrow 2.1\ \text{GHz}$!
Design Issues for Class E

1) Peak voltage across switch reaches $3.6 \times V_{dd}$ for nominal design (so need a high breakdown device)

*In presence of output mismatch this can be $5 \times V_{dd}$ or more (it can be risky without an isolator!)*

2) There is a maximum frequency possible to achieve class E operation, which depends on $C_{out}$ and $V_{dd}$

For Grebbenikov design, this is

$$F_{max} = 0.08 \times \frac{P_{out}}{(C_{out} V_{dd}^2)}$$

To maximize frequency need to minimize $C_{out}$. Chip-on-board could avoid package stray C (but need to get very good die attach for heat sinking)

*(If try to operate at $f$ above $f_{max}$, can get $V=0$ but not $dV/dt=0$ when switch closes).*
Harmonic Load Tuning

Want to achieve high efficiency mode of operation
Heavy compression - near switching mode

Simulated Efficiency vs Harmonic Load Reactance

X2 = \text{Im}(Z_{\text{net}}) \text{ at } 2fo
X3 = \text{Im}(Z_{\text{net}}) \text{ at } 3fo

\begin{align*}
X_1 &= 0
\end{align*}
Harmonic Load Tuning
Simulated Efficiency vs Harmonic Load Reactance

$X_2 = \text{Im}(Z_{\text{net}})$ at $2f_0$
$X_3 = \text{Im}(Z_{\text{net}})$ at $3f_0$

Class $F^{-1}$
Class $F$
Class $B$
Class $F$
Class $F^{-1}$

$X_1 = 0$
Harmonic Load Tuning

Simulated Efficiency vs Harmonic Load Reactance

X1 = RL * 0.7
Harmonic Load Tuning

Simulated Efficiency vs Harmonic Load Reactance

$X_1 = RL \times 0.7$
Efficiency Optimization

Contours of PAE Vs X2, X3 (fixed X1)

Class E point

\[ X1 = RL \times 0.7 \]
Drain Voltage and Current Waveforms*  
For Optimal Matching

Waveforms show "switching" behavior near zero during portion of cycle. Requires even harmonics for voltage.

Best: Overdriven Class "J"  
Intermediate between Class E and Class F-1

- both are

Class B

Class F

Representative simulated results
*Current is through current generator only; Cds capacitive current is de-embedded
PAE vs $X_1/|Z_{L1}|$ and $X_2/|Z_{L1}|$

For $X_3=0$ short

Tradeoff
Inductive $Z_L$ at $f_0$
With Capacitive $Z$ at $2f_0$

$\sim$Class E point
(if $X_3/magRL=0.96$ instead of 0)

Class J region
PAE vs $X_1/|Z_L|$ and $X_2/|Z_L|$ for $X_3=-6$ ~open

Tradeoff
Inductive $Z_L$ at $f_0$
With Capacitive $Z$ at $2f_0$

Class F
PAE vs X1 / |ZL|, X2 / |ZL| and |X3| / |ZL|

Class F

Class E, J region

Class F^-1

Class F
Performance Dependence on Harmonic Content

• **Efficiency increases with harmonics**

<table>
<thead>
<tr>
<th>Class F Harmonics</th>
<th>1 (class A)</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ideal drain efficiency %</td>
<td>50</td>
<td>71</td>
<td>82</td>
<td>87</td>
<td>91</td>
</tr>
<tr>
<td>Power output capability</td>
<td>0.125</td>
<td>0.144</td>
<td></td>
<td>0.151</td>
<td></td>
</tr>
</tbody>
</table>

• **Overdrive the amplifier to generate harmonics**
Linearity Issues for High Efficiency Amplifier Modes

Switching mode amplifier output has constant envelope - determined by power supply, not by switch drive power => used for phase modulated signals only

Class F amplifier can have acceptable linearity - but $\eta$ drops

A key difficulty in optimizing efficiency for waveforms with time varying envelope is:

Need to minimize voltage across transistor, so want $V_t = V_{supply} - V_{rf} = 0$

How to arrange this if $V_{rf}$ varies?