Class E Amplifiers

Part 1: Class E Basics

Dan Tayloe, N7VE
5w Class E 40m Prototype

- Power Amp
- Output Network
- 50 ohm Load
- 6v Regulator
- “Straight Key”
Why Class E?

Class C final, 2w
40 to 45% efficient, ~370 to 410 ma*

Class E final, 2w
88% efficient, ~190 ma*

Almost 50% less TX current required…
Very battery friendly!

* Does not include PA driver. Class E can require very little driver power!
Class E Efficiency Secret

Current vs. time

Switch at low current, Low voltage points ~Zero power at switch!

Voltage vs. time

Fig 1—Conceptual “target” waveforms of transistor voltage and current.

Taken from QEX Jan/Feb 2001
Class E Drain Voltage Waveform

Scale 10v/division
~ 48v at peaks for 5 w, ~40v for 2w
For comparison, Class C devices run only 24v peaks
Class E Design Spread Sheet, 7 MHz

QEX Jan/Feb 2001 Class E Design Equations

Use Q and exact Power to get C1, L2, C2 to standard values

### Class E Output Network Calculator

QL must be larger than 1.788. Normally, Q<5.

### User Inputs

<table>
<thead>
<tr>
<th>P (watts)</th>
<th>Vcc-Vo</th>
<th>F0 (Hz)</th>
<th>QL</th>
<th>C1 (pF)</th>
<th>L1 (uh)</th>
<th>L2 (uh)</th>
<th>C2 (pF)</th>
<th>R Load</th>
<th>XC1</th>
<th>XL1</th>
<th>XL2</th>
<th>XLZ</th>
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<tr>
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Set XL1 above larger than:

- 2813

### Choke

- L1: FT37-43
- L2: T37-2

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<thead>
<tr>
<th>A1</th>
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<tr>
<td>420</td>
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Note: Need to Subtract Transistor output C from C1

### Qc

- Trans C0ut Fix: 0.25
- New C1: 223

### Efficiency Estimate

- 2x BS170
- R0n (ohm) | If (mA) | Efficiency
- 1 | 15 | 87%

April-04

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N7VE / Ozarkcon Class E Presentation
# Class E Design Spread Sheet, 14 MHz

**OEX Jan/Feb 2001 Class E Design Equations**

<table>
<thead>
<tr>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
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**Diagram:**

- **V+**
- **L1**
- **C2**
- **R Load**
- **Q**

**Note:** Need to Subtract Transistor output C from C1

**Efficiency Estimate:** 2× BS170
- Ron (ohms): 11
- Rf (used): 15
- Efficiency: 69%

**Lower efficiency at 14 MHz – 69% Predicted**

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Class E Design Spread Sheet

Excel spread sheet equations...

\[
C_1 \, (pf) = \left( \frac{1e12}{J8 \times 34.2219 \times D8} \right) \times (0.99866 + 0.91424/(E8) - 1.03175/(E8 \times E8)) + \frac{0.6}{(2 \times 2 \times 3.14 \times 3.14 \times D8 \times D8 \times G8/1000000)}
\]

\[
C_2 \, (pf) = \left( \frac{1e12}{J8 \times 2 \times 3.14 \times D8} \right) \times \left( \frac{1}{E8 - 0.104823} \right) \times (1.00121 + 1.01468/(E8 - 1.7879)) - \frac{0.2}{(2 \times 2 \times 3.14 \times 3.14 \times D8 \times D8 \times G8/1000000)}
\]

\[
L_1 \, (uH) = 1000000 \times L8/(2 \times 3.14 \times D8)
\]

\[
L_2 \, (uH) = 1000000 \times J8 \times E8/(2 \times 3.14 \times D8)
\]

\[
R_{load} = (C8 \times C8/B8) \times 0.576801 \times (1.001245 - 0.451759/E8 - 0.402444/(E8 \times E8))
\]

\[
XL1 \geq 30 \times K8
\]

\[
Efficiency = J8/(J8+1.365 \times K27) - 0.01 - (1+ 0.82/E8) \times (1+ 0.82/E8) \times 4 \times \pi^2 \times D8 \times D8 \times L27 \times L27 \times 1e-18/12
\]
Class E Amplifiers

Part 2: No Tune, Goof Proof Class E Amps

Dan Tayloe, N7VE
Problems with Class E QRP Amps

• “Tuning” required to get good efficiency
  • Poor “out of the box” power and efficiency
  • Typical to “tweak” output network coils for best power/efficiency

• Class E finals fail when presented with low impedance loads
  • Low impedance loads cause PA to draw too much current and burn up

• Inexpensive QRP Class E final rated to only 60v (2N7000)
  • Typical PA drain voltage operates in the 40 to 50v range w/ 12v supply
  • Improper antenna mismatch can raise drain voltage, blow the PA
    • 15v supply used with a 12v design could cause problems

• Class E Amps can be unstable into poorly matched loads
  • Tends to “take off”
  • Can lead to device failure
Class E Tuning Problem

- **Class E matching network typically presents a reactive load**
  - I.e., the Class E PA output impedance is *not* purely resistive
  - Reactive characteristic key to Class E efficiency

- **QRP Class E networks need loads in the 10 ohm to 50 ohm (5w to 1w) range**
  - Matching network normally needed to transform to 50 ohm load
  - *1 watt 12v final is a design “sweet spot” – no matching needed*

- **L/C matching networks are typically used to transform driver impedance to 50 ohm load impedance.**
  - This approach does not work well with a reactive drive source!
  - Leads to frequency specific matching network
  - Variations in driver network and matching network elements force the need for “tuning” of the matching networks
No Tune Class E

Solution: Use a broadband matching transformer!

- Broadband Transformer matches 20 ohm PA output to 50 ohm LPF
- Transformer converts Class E reactive impedance without being frequency selective
- However, efficiency is lower (~60%) as measured on 20 & 30m
Class E Load Instability

Solution: Use a lower impedance gate driver!

- **AC family has 24 ma of drive vs 8 ma for HC family**
- **Higher current drive = lower drive source impedance**
- **3x lower source impedance reduces tendency to “flight” with mismatched load**
- **PA gate biased on TX to 3v to help MOSFET turn on harder**
Class E Driver – 74ACT00

Scale: Vertical 2v/div, Horizontal 20 nsec/div
6 to 8v at peaks
Very fast rise+fall times: ~10 nsec total

74ACT00 has 24 ma of drive vs. only 8 ma for the more common 74HCT00 parts
Class E Voltage Limitations

Reduce output when drain voltage gets too high!

- Monitor PA RF drain voltage peaks
- If voltage gets higher than 55v, comparator triggers bias clamp
- Reducing TX gate bias voltage reduces output power to safe limits
Class E Low Load Limitations

Reduce output when PA current gets too high!

- Use resistor voltage drop to sense PA current (~0.175v @ 0.35A)
- Amplify sense resistor voltage by 15x (~2.6v max)
- Use amplified voltage (less 0.6v) to trigger over-voltage circuit
- Trigger reduces PA gate bias & TX output power, limits PA current
No Tune, Goof Proof, Class E Tx

- High impedance over-voltage protection
- Low impedance over-current protection
- “No Tune” Class E output
Current Class E Limitations

• Efficiency of common QRP PA devices (2N7000, BS170) drops off at 14 MHz and above
  - ~80 to 90% efficiency at 10 MHz and below
  - ~70% efficiency at 14 MHz
  - ~60% efficiency using “no tune” approach shown here
  - R/C freq response: Smaller Driver R = Higher Freq response
    - Higher PA drive power can be used to get higher freq PA response
    - Higher PA drive power hurts overall transmitter power saving

• Higher frequency devices available, but more expensive
  - Example: STMicroelectronics PD57006s 900 MHz 5w FET, ~$12
Current Class E Limitations, cont

• Class E operates at a *fixed power* set by Class E output network

• Variable power best done by changing supply voltage

• May be able to reduce power from preset maximum by lowering TX gate drive bias, but at reduced TX efficiency.
Transmitter Spectrum

Scale 10 db/division – legal limit 30 db down

2\textsuperscript{nd} Harmonic \sim 45 \text{ db} down
3\textsuperscript{rd} Harmonic \sim 47 \text{ db} down
All other more than 70 db down
Class E Amplifiers

Part 3: Good & Bad QRP Class E Devices
Or
“Bigger is not Better”

Dan Tayloe, N7VE
Why the IRF510 Makes a Good 5w **Class C** PA

- IRF510 on/off time 70 nsec, good to 14 MHz
- 40 to 45% efficiency typical using broadband, low pass TX output filters
- **5w** output requires **11.1w** input power
  - **6.1w** of heat produced!
  - **33w** IRF510 can take the heat *if proper heat sink is used*
Why the 2N7000 makes a **good** QRP *Class E* final

and the IRF510 *does not*
Good FET – 2N7000, 0.3 to 0.6w

<table>
<thead>
<tr>
<th>Dynamic characteristics</th>
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<tbody>
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<td></td>
<td>$g_{fs}$</td>
<td>forward transconductance</td>
<td>$V_{DS} = 10 \text{ V}; I_D = 200 \text{ mA};$</td>
<td>100</td>
<td>300</td>
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<td>$C_{iss}$</td>
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<td>$C_{rss}$</td>
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<td>$t_{on}$</td>
<td>turn-on time</td>
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<td>$t_{off}$</td>
<td>turn-off time</td>
<td>$V_{GS} = 10 \text{ V}; R_G = 50 \text{ Q};$</td>
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Low input C: 25 pf typical – Low input drive drive!
Fast Turn on/off time: 3+12 nsec = 15 nsec

For class E, need On/Off to be 30% of ½ RF cycle (QEX 1/01)
  • Gives maximum limit of 10 MHz for full efficiency
  • Can be used at 14 MHz at reduced efficiency
    • Measured 80-90% at 7 & 10 MHz, 70% at 14 MHz
**Difficult FET – IRF510, 33w**

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<td>( C_{iss} ) Input Capacitance</td>
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<td>( C_{oss} ) Output Capacitance</td>
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<td>( C_{rss} ) Reverse Transfer Capacitance</td>
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<td>( t_{d(on)} ) Turn-On Delay Time</td>
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<td>( t_r ) Rise Time</td>
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<td>( t_{d(off)} ) Turn-Off Delay Time</td>
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<td>( t_f ) Fall Time</td>
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For class E, need On/Off to be 30% of ½ RF cycle
- Gives **maximum limit of 2 MHz** for full efficiency
- Can speed up by using a lower impedance drive source.
  - **Slam it on, slam it off!** – more drive power needed.

Double driver power hit: High input C & Slow switching time

Higher input C: 190 pf typical – Higher input drive needed!
- *Specs use 24 ohm source here vs. 50 ohm source for 2N7000*

Slower Turn on/off time: \(10+14+28+18\) nsec = \(70\) nsec
Class E Driver Requirements

IRF510 vs. 2N7000

- IRF510, 190 pf input gate C; 2N7000, 25 pf
  - Drive power factor of 7.6x
- IRF510, 25 ohm source; 2n7000, 50 ohm source
  - Drive power factor of 2x
- IRF510, 70 nsec turn on/off; 2n7000, 15 nsec
  - Need 4.67x lower drive impedance to get same speed
  - IRF510 requires 5 ohm driver impedance for 15 nsec on/off

Total drive difference: IRF510 needs 71x more drive power than a single 2N7000

- ~ 0.6w drive for class E IRF511 vs. 17mW for a pair of 2N7000s

IRF510: Good 100w Class E amp, poor 5w amp!
Conclusions

- **Class E saves ~ 50% on TX DC input power to PA**
  - *Low drive power (17 mW vs. 0.6w) saves additional power*
- Class C requires large TO220 PA transistors
- Class E needs only tiny T092/SOT23 300mw/600mw packages
- $0.14 for a new pair of Class E QRP finals!
- Low wasted TX pwr (Heat)
  - *For 5w output, 0.5 to 1w heat (class E) vs. 5 to 6w heat!*
  - Conserves battery life (smaller battery?)
  - Reduces VFO drift
Class E Summary

- **Class E can give up to 88% efficiency**
  - But require tuning to get proper power output

- **Protection circuitry available for Class E finals**
  - Protects against antenna open/short/mismatch problems

- **“No Tune” Class E works, but ~60% efficiently**

- **Bigger is not better for Class E finals**
  - High power MOSFETs (such as the IRF511) require high drive power (71x!), reducing overall rig efficiency.