HIGH-EFFICIENCY RF AND MICROWAVE POWER AMPLIFIERS: HISTORICAL ASPECT AND MODERN TRENDS

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HIGH-EFFICIENCY
RF AND MICROWAVE POWER AMPLIFIERS:
HISTORICAL ASPECT AND MODERN TRENDS

I. POLYHARMONIC CLASS F AND INVERSE CLASS F POWER AMPLIFIERS

II. SWITCHED-MODE CLASS E POWER AMPLIFIERS

III. SWITCHED-MODE CLASS FE POWER AMPLIFIERS
POLYHARMONIC CLASS F AND INVERSE CLASS F POWER AMPLIFIERS

1. Class F: biharmonic and polyharmonic operation modes
2. Class F with quarterwave transmission line
3. Class F: load networks with lumped elements and transmission lines
4. Class F: LDMOSFET power amplifier design examples
5. Inverse Class F: biharmonic and idealized operation modes
6. Inverse Class F: load networks with lumped elements and transmission lines
7. Inverse Class F: LDMOSFET power amplifier design examples
8. Practical high-efficiency Class F power amplifiers
1. Class F: biharmonic and polyharmonic operation modes

Fourier series for:

**rectangular voltage waveform**

\[ \frac{v(\omega t)}{V_0} = 1 + \frac{4}{\pi} \sin \omega t + \frac{4}{3\pi} \sin 3\omega t + \frac{4}{\pi} \sum_{n=5,7,\ldots}^{N} \frac{\sin n\omega t}{n} \]

**half-sinusoidal current waveform**

\[ \frac{i(\omega t)}{I_0} = 1 - \frac{\pi}{2} \sin \omega t - \frac{2}{3} \cos 2\omega t - 2 \sum_{n=4,6,\ldots}^{N} \frac{\cos n\omega t}{n^2 - 1} \]

1. Class F: biharmonic and polyharmonic operation modes

1. Class F: biharmonic and polyharmonic operation modes

For maximally flat waveforms

**Collector Voltage**

\[ V_1 = \frac{9}{8} V_{cc}, \quad V_3 = \frac{1}{8} V_{cc} \]

**Collector Current**

\[ I_1 = \frac{4}{3} I_0, \quad I_2 = \frac{1}{3} I_0 \]

**Optimum Values**

<table>
<thead>
<tr>
<th>Voltage harmonic components</th>
<th>1</th>
<th>1, 3</th>
<th>1, 3, 5</th>
<th>1, 3, 5, 7</th>
<th>1, 3, 5, ... , ( \infty )</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1/2 = 0.500</td>
<td>9/16 = 0.563</td>
<td>75/128 = 0.586</td>
<td>1225/2048 = 0.598</td>
<td>2/(\pi) = 0.637</td>
</tr>
<tr>
<td>1, 2</td>
<td>2/3 = 0.667</td>
<td>3/4 = 0.750</td>
<td>25/32 = 0.781</td>
<td>1225/1536 = 0.798</td>
<td>8/3(\pi) = 0.849</td>
</tr>
<tr>
<td>1, 2, 4</td>
<td>32/45 = 0.711</td>
<td>4/5 = 0.800</td>
<td>5/6 = 0.833</td>
<td>245/288 = 0.851</td>
<td>128/45(\pi) = 0.905</td>
</tr>
<tr>
<td>1, 2, 4, 6</td>
<td>128/175 = 0.731</td>
<td>144/175 = 0.823</td>
<td>6/7 = 0.857</td>
<td>7/8 = 0.875</td>
<td>512/175(\pi) = 0.931</td>
</tr>
<tr>
<td>1, 2, 4, ... , ( \infty )</td>
<td>(\pi/4) = 0.785</td>
<td>9(\pi/32) = 0.884</td>
<td>75(\pi/256) = 0.920</td>
<td>1225(\pi/4096) = 0.940</td>
<td>(1 = 1.000)</td>
</tr>
</tbody>
</table>
1. Class F: idealized operation mode

**Ideal current waveform**

\[ I_0 = \frac{I_{\text{max}}}{2} \]  - fundamental current component

\[ V_1 = \frac{4V_{cc}}{\pi} \]  - fundamental voltage component

\[ I_0 = \frac{I_{\text{max}}}{\pi} \]  - dc current component

\[ P_1 = \frac{V_{cc}I_{\text{max}}}{\pi} \]  - fundamental output power

\[ P_0 = V_{cc}I_0 \]  - dc supply power

\[ \eta = \frac{P_1}{P_0} = 100\% \]  - collector/drain efficiency

**Harmonic impedance conditions:**

\[ Z_1 = R_1 = \frac{8V_{cc}}{\pi I_{\text{max}}} = \frac{8V_{cc}}{\pi^2 I_0} \]

\[ Z_n = 0 \] for even \( n \)

\[ Z_n = \infty \] for odd \( n \)
2. Class F with quarterwave transmission line

Assumptions for transistor:
- ideal switch: no parasitic elements
- half period is on, half period is off: 50% duty cycle

Assumptions for load:
- sinusoidal current: ideal $L_0C_0$-circuit tuned to fundamental

\[
\begin{align*}
i(\omega t) &= I_R \sin \omega t & \text{- load current} \\
v(\omega t) &= 2V_{cc} - v(\omega t + \pi) & \text{- collector voltage} \\
i(\omega t) &= I_R (\sin \omega t + |\sin \omega t|) & \text{- collector current}
\end{align*}
\]

\[
i_T(\omega t) = i_T(\omega t + \pi) = I_R |\sin \omega t| & \text{- transmission-line current}
\]

\[
\begin{align*}
i_T/I_0 &
\end{align*}
\]
3. Class F: second current and third voltage harmonic peaking

**Load network**

Output reactive admittance:

\[
\text{Im}(Y_{\text{net}}) = \omega C_{\text{out}} - \frac{1 - \omega^2 L_2 C_2}{\omega L_1 \left(1 - \omega^2 L_2 C_2\right) + \omega L_2}
\]

Three harmonic impedance conditions:

\[
\begin{align*}
\text{Im}Y_{\text{net}}(\omega_0) &= 0 \\
\text{Im}Y_{\text{net}}(2\omega_0) &= \infty \\
\text{Im}Y_{\text{net}}(3\omega_0) &= 0
\end{align*}
\]

**Circuit parameters**

\[
L_1 = \frac{1}{6\omega_0^2 C_{\text{out}}}, \quad L_2 = \frac{5}{3} L_1, \quad C_2 = \frac{12}{5} C_{\text{out}}
\]

Matching circuit with high impedances at harmonics

**S_{21} simulation (f_0 = 500 MHz)**

\[
S_{21}, \text{ dB}
\]

\[
Q_{\text{ind}} = 20
\]
3. Class F: even current and third voltage harmonic peaking

**Load network**

Harmonic impedance conditions at collector (drain):

\[
\text{Im} Y_{\text{net}}(\omega_0) = 0 \\
\text{Im} Y_{\text{net}}(2n\omega_0) = \infty \\
\text{Im} Y_{\text{net}}(3\omega_0) = 0
\]

**S\textsubscript{21} simulation (f\textsubscript{0} = 500 MHz)**

**Circuit parameters:**

\[
\theta_1 = \frac{\pi}{2}, \quad \theta_3 = \frac{\pi}{6}
\]

\[
\theta_2 = \frac{1}{3} \tan^{-1} \left( \frac{1}{3Z_0 \omega C_{\text{out}}} \right)
\]

- ideal transmission lines
3. Class F: even current and third voltage harmonic peaking

Load network with impedance matching

\[ V_{dd} \]
\[ C_{bypass} \]
\[ \lambda/4 \]
\[ Z_{o3} \]
\[ \lambda/12 \]
\[ Z_{02}, \theta_2 \]
\[ C_{out} \]
\[ R_L \]
\[ R_{out} \]
\[ Z_{net} \]

Normalized parameters:

\[ m = \frac{R_L}{R_{out}} \quad q = \frac{R_L}{Z_{o3}\sqrt{3}} \]

\[ n = \omega C_{out} Z_{02} \]
4. Class F: LDMOSFET power amplifier design example

500 MHz Class F power amplifier with lumped elements

Drain voltage and current waveforms

LDMOSFET:
gate length 1.25 um
gate width 7x1.44 mm

- inductance Q-factor = \infty
- efficiency - 82%
- linear power gain > 16 dB

- inductance Q-factor = 30
- efficiency - 71%
- linear power gain > 14 dB
4. Class F: LDMOSFET power amplifier design example

500 MHz Class F power amplifier with transmission lines

**Drain voltage and current waveforms**

**Output matching**

**LDMOSFET:**
- gate length 1.25 um
- gate width 7x1.44 mm

- T-matching circuit for output impedance transformation
- output power - 39 dBm (8 W)
- collector efficiency - 76%
- linear power gain > 16 dB
5. Inverse Class F: biharmonic and idealized operation modes

Second-harmonic peaking

Inverse voltage and current waveforms

Fourier series for:

**rectangular current waveform**

\[
\frac{i(t)}{I_0} = 1 + \frac{4}{\pi} \sin \omega t + \frac{4}{3\pi} \sin 3\omega t + \frac{4}{\pi} \sum_{n=5,7,...}^{N} \frac{\sin n\omega t}{n}
\]

**half-sinusoidal voltage waveform**

\[
\frac{v(t)}{V_0} = 1 - \frac{\pi}{2} \sin \omega t - \frac{2}{3} \cos 2\omega t - 2 \sum_{n=4,6,...}^{N} \frac{\cos n\omega t}{n^2 - 1}
\]

A. I. Kolesnikov, “A New Method to Improve Efficiency and to Increase Power of Transmitter (in Russian),” *Master Svyazi*, pp. 27-41, June 1940
5. Inverse Class F: idealized operation mode

Concept of inverse Class F mode was reintroduced for low voltage power amplifiers designed for monolithic applications (less collector current)

Dual to conventional Class F with mutually interchanged current and voltage waveforms

- fundamental current
- fundamental voltage
- fundamental output power
- dc output power
- ideal collector/drain efficiency

Harmonic impedance conditions:

\[ Z_1 = R_1 = \frac{\pi V_{\text{max}}}{8 I_0} = \frac{\pi^2 V_{\text{cc}}}{8 I_0} \]

\[ Z_n = 0 \quad \text{for odd } n \]

\[ Z_n = \infty \quad \text{for even } n \]
5. Inverse Class F with quarterwave transmission line

- device is driven to operate as switch
- zero impedances at odd harmonic components

overall quarterwave transmission line as infinite set of series resonant circuits
- sinusoidal current: shunt $L_0C_0$-circuit tuned to fundamental
- quarterwave transmission line as impedance transformer

\[ R_1 = \frac{Z_0^2}{R_L} \]
6. Inverse Class F: second current and third voltage harmonic peaking

Load network

Circuit parameters:

\[ \theta_1 = \frac{\pi}{3}, \quad \theta_3 = \frac{\pi}{4} \]

\[ \theta_2 = \frac{1}{2} \tan^{-1} \left[ \left( 2Z_0 \omega C_{\text{out}} + \frac{1}{\sqrt{3}} \right)^{-1} \right] \]

Harmonic impedance conditions at collector (drain):

- \( \text{Im} Y_{\text{net}}(\omega_0) = 0 \)
- \( \text{Im} Y_{\text{net}}(2\omega_0) = 0 \)
- \( \text{Im} Y_{\text{net}}(3\omega_0) = \infty \)

S_{21} simulation \( (f_0 = 500 \text{ MHz}) \)

\[ S_{21}, \text{ dB} \]

f, GHz

- ideal transmission lines
7. Inverse Class F: LDMOSFET power amplifier design example

500 MHz inverse Class F power amplifier with transmission lines

- Output power - 39 dBm or 8 W
- Collector efficiency - 71%

Drain voltage and current waveforms

Load network with output matching
Optimum load network resistances at fundamental for different classes of operation

**Class B:**
\[ R^{(B)} = \frac{V_{cc}}{I_1} = \frac{V_{cc}^2}{2P_1} \]

**Class F:**
\[ R^{(F)} = \frac{4}{\pi} \frac{V_{cc}}{I_1} = \frac{4}{\pi} R^{(B)} \]

**Inverse Class F:**
\[ R^{(invF)} = \frac{\pi}{2} \frac{V_{cc}}{I_1} = \frac{\pi^2}{8} R^{(F)} = \frac{\pi}{2} R^{(B)} \]

Load resistance in inverse Class F is the highest (1.6 times larger than in Class B)

Less impedance transformation ratio and easier matching procedure
8. Practical high-efficiency RF and microwave Class F power amplifiers

Class F GaN HEMT power amplifier with input harmonic control

Class AB biasing with small quiescent current

RC-circuits at the input for stable operation

Characteristic impedance $Z_2$ and electrical length $\theta$ is tuned to form third-harmonic tank with output device capacitance $C_{ds}$

Characteristic impedances $Z_2$ and $Z_3$ are chosen to provide conjugate impedance matching at fundamental

85% power-added efficiency for 16.5 W at 2 GHz

8. Practical high-efficiency RF and microwave Class F power amplifiers

Inverse Class F LDMOSFET power amplifier with quarterwave line

- **Class AB biasing with small quiescent current**
- **L-type input matching circuit with shunt variable capacitance**
- **L-type low-pass output matching circuit with shunt variable capacitance**

60% drain efficiency for 13 W at 1.78 GHz

II. SWITCHED-MODE CLASS E POWER AMPLIFIERS

1. Effect of detuned resonant circuit

2. Basic Class E with shunt capacitance

3. Generalized Class E load network with finite dc-feed inductance

4. Parallel-circuit Class E

5. Class E approximation with transmission lines

6. Class E with quarterwave transmission line

7. Broadband Class E circuit design

8. Practical RF and microwave Class E power amplifiers
1. Effect of detuned resonant circuit

- Anode efficiency of 92-93% for resonant-circuit phase angles of 30-40°: inductive impedance at fundamental and capacitive at harmonics

- Resonant frequency \( f \approx (1.4-1.5)f_0 \)
  
  \[ f_0 \]  
  fundamental frequency

- Load current lags collector voltage so that series LC\(_0\)-circuit must appear inductive at operating frequency

- Pulsed excitation with highest efficiency for conduction angles less than 180°

- Collector efficiency of 94% for 20 W 500 kHz bipolar power amplifier with 50% duty cycle


2. Basic Class E with shunt capacitance

**Idealized assumptions for analysis:**

- transistor has zero saturation voltage, zero on-resistance, infinite off-resistance and its switching action is instantaneous and lossless
- RF choke allows only dc current and has no resistance
- total shunt capacitance is assumed to be linear
- reactive elements in load network are lossless
- loaded quality factor $Q_L$ of series fundamentally tuned resonant $L_0C_0$-circuit is infinite to provide pure sinusoidal current flowing into load
- for optimum operation 50% duty cycle is used

**Idealized optimum or nominal conditions**

\[
\left. \nu(\omega t) \right|_{\omega t = 2\pi} = 0
\]

\[
\left. \frac{d\nu(\omega t)}{d\omega t} \right|_{\omega t = 2\pi} = 0
\]
2. Basic Class E with shunt capacitance

**Optimum circuit parameters:**

\[ L = 1.1525 \frac{R}{\omega} \]  - series inductance

\[ C = 0.1836 \frac{1}{\omega R} \]  - shunt capacitance

\[ R = 0.5768 \frac{V_{cc}^2}{P_{out}} \]  - load resistance

**Optimum phase angle at fundamental seen by switch:**

\[ \phi = \tan^{-1}\left(\frac{\omega L}{R}\right) - \tan^{-1}\left(\frac{\omega CR}{1 - \frac{\omega L}{R} \omega CR}\right) \approx 35.945^\circ \]
2. Basic Class E with shunt capacitance

Power loss due to non-zero saturation resistance

\[
\frac{P_{\text{sat}}}{P_{\text{dc}}} \approx \frac{8}{3} \frac{r_{\text{sat}} P_{\text{out}}^2}{V_{\text{cc}}^2} \approx 1.365 \frac{r_{\text{sat}}}{R}
\]

Power loss due to finite switching time

\[
\frac{P_{\text{sw}}}{P_{\text{dc}}} \approx \frac{\tau_{\text{sw}}^2}{12}
\]

For \( \tau_{\text{sw}} = 0.35 \) or 20°,
only 1% efficiency loss

For nonlinear capacitances represented by abrupt junction collector capacitance with \( \gamma = 0.5 \),
peak collector voltage increases by 20%

Non-ideal switch

Nonlinear capacitance
3. Generalized Class E load network with finite dc-feed inductance

- **load network consists of dc-feed inductance** $L$ supplying also dc current, shunt capacitor $C$, series reactance $X$, bondwire inductance $L_b$, series fundamentally tuned $L_0C_0$ resonant circuit, and load $R$

- **shunt capacitor** $C$ can represent intrinsic device output capacitance and external circuit capacitance

- **active device is considered as ideal switch to provide instantaneous device switching between its on-state and off-state operation conditions**

- **series reactance** $X$ can be positive (inductance), zero and negative (capacitive)

**Optimum ideal voltage conditions across switch:**

\[
\begin{align*}
&v(\omega t)\big|_{\omega t=2\pi} = 0 \\
&\frac{dv(\omega t)}{d\omega t}\big|_{\omega t=2\pi} = 0
\end{align*}
\]

\[i_R(\omega t) = I_R \sin(\omega t + \varphi) \quad - \text{sinusoidal current in load}\]
3. Generalized Class E load network with finite dc-feed inductance

\[ \omega^2(L + L_b)LC \frac{d^2v(\omega t)}{d(\omega t)^2} + v(\omega t) - V_{cc} - \omega LI_R \cos(\omega t + \varphi) = 0 \]

- second-order differential equation

where

\[ \frac{v(\omega t)}{V_{cc}} = C_1 \cos(q \omega t) + C_2 \sin(q \omega t) + 1 - \frac{q^2 p}{1 - q^2} \cos(\omega t + \varphi) \]

and coefficients \( C_1 \) and \( C_2 \) are defined from initial conditions

\[ \omega CR = 1 / q^2 \left( 1 + \frac{L_b}{L} \right) \frac{\omega L}{R} \]

- shunt capacitance

\[ \frac{\omega L}{R} = p \left( 1 + \frac{L_b}{L} \right) / \left( \frac{\pi}{2p} + \frac{2}{\pi} \cos \varphi - \sin \varphi \right) \]

- dc-feed inductance

\[ R = \frac{1}{2\pi^2} \left( \frac{\pi^2}{2p} + 2 \cos \varphi - \pi \sin \varphi \right)^2 \frac{V_{cc}^2}{P_{out}} \left( 1 + \frac{L_b}{L} \right)^2 \]

- load resistance
3. Generalized Class E load network with finite dc-feed inductance

**Normalized load network parameters versus** $q = 1/\omega \sqrt{LC}$, $L_b = 0$

- $q \leq 0.5$: close to Class E with shunt capacitance with positive (inductive) series reactance ($X > 0$)
- $q = 1.412$: parallel-circuit Class E with zero reactance ($X = 0$) – maximum load resistance $R$
- $q = 1.468$: maximum shunt capacitance $C$ (maximum operating frequency $f_{\text{max}}$) with negative (capacitive) reactance ($X < 0$)
To define three unknown parameters \( q \), \( \varphi \) and \( p \), two ideal optimum conditions and third equation for zero reactive part of fundamental Fourier component are applied resulting to system of three algebraic equations:

\[
\begin{align*}
\left. v(\omega t) \right|_{\omega t=2\pi} &= 0, \\
\left. \frac{dv(\omega t)}{d\omega t} \right|_{\omega \phi=2\pi} &= 0 \\
V_X &= -\frac{1}{\pi} \int_0^{2\pi} v(\omega t) \cos(\omega t + \varphi) d(\omega t) = 0
\end{align*}
\]

Optimum circuit parameters:

- parallel inductance
  \[ L = 0.732 \frac{R}{\omega} \]
- parallel capacitance
  \[ C = \frac{0.685}{\omega R} \]
- load resistance: highest value in Class E
  \[ R = 1.365 \frac{V_{cc}^2}{P_{out}} \]

\[ q = 1.412 \quad p = 1.210 \quad \varphi = 15.155^\circ \]
4. Parallel-circuit Class E

**Load current**

![Graph of load current](image)

**Inductive impedance at fundamental**

\[
\phi = \tan^{-1}\left(\frac{I_X}{I_R}\right) = \tan^{-1}\left(\frac{R}{\omega L - \omega RC}\right) = 34.244^\circ
\]

**Collector voltage**

![Graph of collector voltage](image)

**Current through capacitance**

![Diagram of circuit with current through capacitance](image)

**Collector current**

![Graph of collector current](image)
5. 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

- Transmission-line characteristic impedances are chosen to provide optimum inductive impedance seen by device output at fundamental

5. Class E with transmission lines: approximation

Transmission-line parallel-circuit Class E GaAs HBT power amplifier for handset application

- Parameters of parallel transmission line is chosen to realize optimum inductive impedance at fundamental
- Output matching circuit consisting of series microstrip line with two shunt capacitors should provide capacitive reactances at second and third harmonics
6. Class E with quarterwave transmission line

**Optimum voltage conditions across switch:**

\[
\begin{align*}
\nu(\omega t)_{\omega t=2\pi} &= 0 \\
\frac{d\nu(\omega t)}{d\omega t}_{\omega t=2\pi} &= 0
\end{align*}
\]

- **sinusoidal load current**
- **50% duty cycle**

\[
\frac{d^2i_C(\omega t)}{d(\omega t)^2} + \frac{q^2}{2}i_C(\omega t) + I_R \sin(\omega t + \varphi) = 0
\]

**Boundary conditions:**

\[
\begin{align*}
i_C(\omega t)_{\omega t=\pi} &= 2i_R(\pi) \\
\frac{di_C(\omega t)}{d(\omega t)}_{\omega t=\pi} &= \frac{V_{cc}}{\omega L} - I_R \cos(\varphi)
\end{align*}
\]

\[
p = \frac{\omega LI_R}{V_{cc}} \\
q = \frac{1}{\omega \sqrt{LC}}
\]

- **q** = 1.649  
- **p** = 1.302  
- **\varphi** = -40.8°
6. Class E with quarterwave transmission line

**Optimum circuit parameters:**

- **Series inductance**
  
  \[ L = 1.349 \frac{R}{\omega} \]

- **Shunt capacitance**
  
  \[ C = \frac{0.2725}{\omega R} \]

- **Load resistance**
  
  \[ R = 0.465 \frac{V_{cc}^2}{P_{out}} \]

**Load current**

**Collector voltage**

**Current through capacitance**

**Collector current**

**Current through transmission line**
6. Class E with quarterwave transmission line

Optimum impedances at fundamental and harmonics for different Class E load networks

<table>
<thead>
<tr>
<th>Class E load network</th>
<th>$f_0$ (fundamental)</th>
<th>$2nf_0$ (even harmonics)</th>
<th>$(2n+1)f_0$ (odd harmonics)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Class E with shunt capacitance</td>
<td><img src="Circuit1" alt="Circuit Diagram" /></td>
<td><img src="Circuit2" alt="Circuit Diagram" /></td>
<td><img src="Circuit3" alt="Circuit Diagram" /></td>
</tr>
<tr>
<td>Class E with parallel circuit</td>
<td><img src="Circuit4" alt="Circuit Diagram" /></td>
<td><img src="Circuit5" alt="Circuit Diagram" /></td>
<td><img src="Circuit6" alt="Circuit Diagram" /></td>
</tr>
<tr>
<td>Class E with quarterwave transmission line</td>
<td><img src="Circuit7" alt="Circuit Diagram" /></td>
<td><img src="Circuit8" alt="Circuit Diagram" /></td>
<td><img src="Circuit9" alt="Circuit Diagram" /></td>
</tr>
</tbody>
</table>
7. Broadband Class E circuit design

Reactance compensation load network

Input load network admittance

\[
Y_{in} = \left( j\omega C + \frac{1}{j\omega L} + \frac{1}{R + j\omega L_0} \right)
\]

\[
\omega' = \omega \left( 1 - \frac{\omega_0^2}{\omega^2} \right) \quad \omega_0 = \frac{1}{\sqrt{L_0C_0}}
\]

To maximize bandwidth:

\[
\left. \frac{d}{d\omega} \text{Im} Y_{in}(\omega) \right|_{\omega=\omega_0} = 0
\]

\[
C + \frac{1}{\omega^2 L} - \frac{2L_0}{R^2} = 0
\]

Optimum parameters for series resonant circuit in Class E mode

\[
L_0 = 1.026 \frac{R}{\omega}
\]

\[
C_0 = \frac{1}{\omega^2 L_0}
\]

1 - impedance provided by series \( L_0C_0 \) resonant circuit
2 - impedance provided by parallel \( LC \) resonant circuit

- summation of reactances with opposite slopes results in constant load phase over broad frequency range

Reactance compensation principle

Device output

\( Z_{in} \)

\( L \)

\( R \)

\( C \)

\( L_0 \)

\( C_0 \)
7. Broadband Class E circuit design

*Broadband Class E power amplifier with reactance compensation*

\[ f_0 = 120...180 \text{ MHz} \]

**Drain voltage and current waveforms**

**LDMOSFET:**
- gate length 1.25 um
- gate width 7x1.44 mm

1 - drain efficiency > 71%
2 - power gain > 9.5 dB

- input power - 1 W
- input VSWR < 1.4
- gain flatness \( \leq \pm 0.3 \)
High power LDMOSFET RF Class E power amplifier

- Class B with zero quiescent current
- Series inductance and ferrite 4:1 transformer is required to match device input impedance
- L-type output transformer to match optimum 1.5 Ω output impedance to 50 Ω load
- Quality factor of resonant circuit was chosen to be sufficiently low (∼ 5) to provide some frequency bandwidth operation and to reduce sensitivity to resonant circuit parameters
- Required value of Class E shunt capacitance is provided by device intrinsic 38 pF capacitance and external 55 pF capacitance

70% drain efficiency for 54 W at 144 MHz

8. Practical RF and microwave Class E power amplifiers

Transmission-line low-harmonic GaN HEMT Class E power amplifier

- \(\pi\)-type low-pass input matching
- Class C biasing
- Short transmission line \(TL_1\) provides required series inductive reactance
- Output open-circuit stubs are tuned to be quarterwave at 2\(^{nd}\) and 3\(^{rd}\) harmonics and capacitive at fundamental
- Characteristic impedances \(Z_2\) and \(Z_3\) are chosen to provide load matching together with series line \(TL_1\)

Input second-harmonic termination circuit is used to provide input quasi-square voltage waveform minimizing device switching time

74% power-added efficiency for 11.4 W at 2 GHz

III. SWITCHED-MODE CLASS FE POWER AMPLIFIERS

1. Basic load network and operation principle

2. Load network parameters and voltage and current waveforms

3. Design approximations with second-harmonic control (Class EF$_2$) and third-harmonic control (Class E/F$_3$)
1. Basic load network and operation principle

- Class E idealized optimum conditions applied to Class F mode affected by shunt parasitic capacitance, with added series inductance

- Symmetrizing action of shunt quarterwave line provides its voltage inverter mode resulting in similar waveform as in Class D or Class DE: it stores voltage waveform in traveling wave along its length which returns delayed by one-half fundamental period and inverted due to reflection from short-circuited end

- Transistor has zero saturation voltage, zero on-resistance, infinite off-resistance and its switching action is instantaneous and lossless
1. Basic load network and operation principle

- **switch is turned on**

- **switch is turned off**

- **dead time during charging or discharging process when current flow through shunt capacitance**

- **half-wave symmetry of transmission-line current waveform: line attempts to do same work in first and second halves of cycle**

- **zero initial phase and duty cycle D < 0.5**
2. Load network parameters and voltage and current waveforms

Optimum circuit parameters:

\[ R = \frac{2 \left( 1 + \cos \tau_d \right)^2}{\pi^2} \frac{V_{cc}^2}{P_{out}} \]  
- load resistance

\[ L = \frac{\tau_d - \sin \tau_d \cos \tau_d R}{\sin^2 \tau_d} \frac{1}{\omega} \]  
- series inductance

\[ C = \frac{\sin^2 \tau_d}{\pi} \frac{1}{\omega R} \]  
- shunt capacitance

\( \tau_d \) - dead time

Optimum impedances at fundamental and harmonics for Class F, Class E and Class FE load networks

<table>
<thead>
<tr>
<th>High-efficiency mode</th>
<th>( f_0 ) (fundamental)</th>
<th>( 2nf_0 ) (even harmonics)</th>
<th>( (2n+1)f_0 ) (odd harmonics)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Class F with quarterwave line</td>
<td></td>
<td>short</td>
<td>open</td>
</tr>
<tr>
<td>Class E with shunt capacitance</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Class FE with quarterwave line</td>
<td></td>
<td>short</td>
<td></td>
</tr>
</tbody>
</table>
3. Design approximations with second-harmonic control (Class EF₂) and third-harmonic control (Class E/F₃)

Class $E₂F$ (or $F₂E$) power amplifier

Idealized optimum conditions:

$$v(\omega t)\big|_{\omega t=2\pi} = 0$$

$$\frac{dv(\omega t)}{d\omega t} \big|_{\omega t=2\pi} = 0$$

- Transistor has zero saturation voltage, zero on-resistance, infinite off-resistance and its switching action is instantaneous and lossless.

- Ideal Class E load network with shunt capacitance.

- Series resonant $L₂C₂$ circuit tuned to second harmonic.

3. Design approximations with second-harmonic control (Class EF₂) and third-harmonic control (Class E/F₃)

**Class E/F₃ power amplifier**

Idealized optimum conditions

\[
v(\omega t)\big|_{\omega t=2\pi} = 0
\]

\[
\frac{dv(\omega t)}{d\omega t} \bigg|_{\omega t=2\pi} = 0
\]

- Transistor has zero saturation voltage, zero on-resistance, infinite off-resistance and its switching action is instantaneous and lossless
- Ideal Class E load network with shunt capacitance
- Series resonant \( L_3C_3 \) circuit tuned to third harmonic

References

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