Thesis Presentation for:

DESIGN AND IMPLEMENTATION OF A COMPACT HIGHLY EFFICIENT 472KHZ RADIO FREQUENCY GENERATOR FOR ELECTROSURGERY

Submitted by
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Masters of Science Electrical Engineering
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Presentation Overview

• Design Target

• Key Findings

• Conclusions

• Future Directions
Design Target

• Joint adventure with CSU and Covidien

• (Primary Thesis Work) Covidien sponsored the work for a Electrosurgery Generator

• (Earlier Work) CSU Plasma High Voltage Generator for Liquid and Gas Loads
Design Target

- Build and Demonstrate A 100-150W RF generator (RFG-1), suitable operation for electrosurgery

- Dynamic Load balancing for:
  - Electrosurgery load (resistive 20 to 500 Ohm)
  - Plasma load (Gas and Liquid) (Reactive)

- Reduce form factor from conservation of valuable operating room space,
  - commercially available unit is 11.1cm x 35.6xm x 43.9cm (~17347cm³)
  - 8.1kg
# Target Specifications for Electrosurgery Generator

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Input Voltage Range</td>
<td>42 to 60 Vdc</td>
</tr>
<tr>
<td>Output Frequency at 50 Ohm</td>
<td>472kHz</td>
</tr>
<tr>
<td>Frequency Variation</td>
<td>±23kHz</td>
</tr>
<tr>
<td>Max output power</td>
<td>112 Watts at 20 Ohms</td>
</tr>
<tr>
<td>Output power derating</td>
<td>13 Watts at 500 Ohms</td>
</tr>
<tr>
<td>Output Load Impedance</td>
<td>20 to 500 Ohms</td>
</tr>
<tr>
<td>Max output voltage at no load</td>
<td>250 Volts peak to peak</td>
</tr>
<tr>
<td>Max output current at full load</td>
<td>2.5A RMS</td>
</tr>
<tr>
<td>Efficiency</td>
<td>&gt;80% at full power</td>
</tr>
<tr>
<td>Package size</td>
<td>77mm x 102mm x 51mm (400cm³)</td>
</tr>
</tbody>
</table>
## Target Specifications for Plasma Generator

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Additional Output Transformer</td>
<td>External</td>
</tr>
<tr>
<td>High Output Voltage</td>
<td>1000 V RMS</td>
</tr>
<tr>
<td>Output Load Impedance</td>
<td>Variable, reactive</td>
</tr>
<tr>
<td>Load Type</td>
<td>Plasma, Gas Plasma, Liquid</td>
</tr>
</tbody>
</table>
Electrosurgery Load
Max load (20Ω)

Plasma Load
Gas Load (~512Ω)
Challenges

• Selection amplifier topology

• Choice of magnetics for operation at 500kHz

• Design high frequency transformer/inductor windings

• Choice of capacitor for resonant operation at 500kHz
Amplifier Selection

• Goal 1
  – Eliminate the need for forced air cooling.

• Means
  – Air movement in operating room is not desired
  – Ultra high efficient topology

• Goal 2
  – To reduce required volume

• Means
  – Space/volume in a operating room is expensive
  – Simple amplifier topology
Amplifier Topologies

• Several amplifier topologies were considered based on simplicity, efficiency, distortion and required volume of space
  – Class-A, Most simple, ~25%, low THD, low volume
  – Class-B, moderate simple, ~78%, moderate distortion, moderate volume
  – Class-AB, moderate simple, ~78%, low distortion, moderate volume
  – Class-C, Simple, ~78%, HIGH distortion, moderate volume
  – Class-D, Simple, >90%, moderate distortion, low volume
  – Class-E/F, Simple, >90%, HIGH distortion, low volume
  – Class-G, Complex, ~78%, low distortion, moderate volume

• Final selection was a saturation type of amplifier similar to a Class –D with adjustable supply rails for amplitude control
Power Source Topologies for Rail / Amplitude Control

• Same selection process as amplifier (Efficiency, Complexity, Volume)
  – Boost, 70-80%, Simple, Low Volume
  – Buck, 80-90%, Simple, Low Volume
  – Buck-Boost, 60-70%, More complex, High Volume
  – Synchronous Buck, Low 90%, Moderate Complex, Moderate Volume

• Final selection was a Synchronous Buck
HV Transformer Prototype
“Preliminary Design Work”

• Modified Class-D amplifier to produce a 500kHz output.
• Square wave output
• Quick prototype based on a early design target for a high voltage output 1kVpp.
Preliminary Design Work

• Lessons Learned
  – Pro: Proved that rail amplitude control will work
  – Pro: Simplicity
  – Con: High output ringing
  – Con: High output distortion
The Concept

- Synchronous Buck for amplitude control
  - estimated efficiency 92%
- Resonant Amplifier for low distortion and high efficiency
  - estimated efficiency, 95%
- Output Transformer for amplification and isolation
  - estimated efficiency, 95%

- Total estimated design efficiency, 83%
  - Final testing showed ~72%
Resonant Amplifier Stage

- Operating at resonant means ZVS and ZCS

- Resonant point is based on L1, C1, and transformer inductances
Model of Resonant Amplifier

- $Z_{\text{Load}}$ is time variant
Effect of Transformer Magnetization Inductance

- The parallel reactance of the magnetization inductance increases losses and impacts efficiency at lighter loads.

- Increases losses and impacts efficiency at lighter loads.
Transformer Challenge, Core

- Key concern is core losses
- Core losses are specified on core losses per volume
- Larger sized cores for use at 500kHz are not that common

Comparison
- 3F35 is optimum

<table>
<thead>
<tr>
<th>Core Material</th>
<th>Loss at 100C 50mT</th>
<th>Loss at 100C 100mT</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ve = 7.64e-6 m³</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3C96</td>
<td>1.91 Watts</td>
<td>8.40 Watts</td>
</tr>
<tr>
<td>3F3</td>
<td>2.14 Watts</td>
<td>9.17 Watts</td>
</tr>
<tr>
<td>3F35</td>
<td>0.65 Watts</td>
<td>5.42 Watts</td>
</tr>
</tbody>
</table>
Transformer Windings Wire

• Must have low AC-resistance

• To minimize low losses to achieve high efficiency

• Optimize wire size for skin-effect (472kHz is 31 AWG).

• 31 AWG would not handle the current

• The approach of use parallel strands for current was tested during the Preliminary Design Work

• It was found at lower strand count the losses were acceptable, but would not be acceptable at the required strand count for this design
Proximity Losses

• Optimum wire size for 472kHz is 31AWG
• Several parallel strands are needed for the high current
  – 2.5A RMS ➔ 27 strands
• Resulting in high proximity losses
Solution for Proximity Losses

- Litz-Wire, uses a special weaving and bundling to overcome proximity effect

- Using the manufacturers recipe "New England Wire Company"

- Optimum form for 500kHz is Round Type-2

- Litz Wire AC-Resistance
  - Secondary 2.5 A RMS → 5X3/27/44 → 7.60 (AC) Ohm / 1kft
  - Primary 10.0 A RMS → 5X5X3/22/44 → 1.92 (AC) Ohm / 1kft
## Transformer, Summary

<table>
<thead>
<tr>
<th>Core material</th>
<th>Ferroxcube 3F35</th>
</tr>
</thead>
<tbody>
<tr>
<td>Form factor</td>
<td>Ferroxcube ETD34/17/11</td>
</tr>
<tr>
<td>Primary wire</td>
<td>Litz 5X5X3/22/44</td>
</tr>
<tr>
<td>Secondary wire</td>
<td>Litz 5X3/27/44</td>
</tr>
<tr>
<td>Turns Ratio</td>
<td>N = 4</td>
</tr>
<tr>
<td>Primary Turns</td>
<td>Tpri = 1</td>
</tr>
<tr>
<td>Secondary Turns</td>
<td>Tsec = 4</td>
</tr>
<tr>
<td>Primary Inductance</td>
<td>Lpri = 1.85 uH ±25%</td>
</tr>
<tr>
<td>Secondary Inductance</td>
<td>Lsec = 29.6uH ±25%</td>
</tr>
<tr>
<td>Primary AC resistance</td>
<td>2.279 mOhms</td>
</tr>
<tr>
<td>Secondary AC resistance</td>
<td>12.112 mOhms</td>
</tr>
<tr>
<td><strong>Core material</strong></td>
<td>Ferroxcube 3F35</td>
</tr>
<tr>
<td>-------------------</td>
<td>-----------------</td>
</tr>
<tr>
<td><strong>Form factor</strong></td>
<td>Ferroxcube ETD34/17/11</td>
</tr>
<tr>
<td><strong>Winding wire</strong></td>
<td>Litz 5X3/27/44</td>
</tr>
<tr>
<td><strong>Inductance</strong></td>
<td>16.65uH</td>
</tr>
<tr>
<td><strong>Turns</strong></td>
<td>Tpri = 3</td>
</tr>
<tr>
<td><strong>Wire Length</strong></td>
<td>$7.1 + 8.0 = 15.1$ inches</td>
</tr>
<tr>
<td><strong>DC resistance</strong></td>
<td>2.414 mOhms</td>
</tr>
<tr>
<td><strong>AC-DC resistance ratio</strong></td>
<td>1.375</td>
</tr>
<tr>
<td><strong>AC resistance</strong></td>
<td>3.318 mOhms</td>
</tr>
</tbody>
</table>
Capacitor Selection

• Primary loss mechanism is ESR
  – ESR impacts thermal stability from self-heating

• Capacitance shift (stability)
  – Temperature drift
  – Voltage, dielectric stress

• Both are related to dielectric material
  – X7R
  – NP0/C0G
Capacitor, ESR

• ESR is related to
  – Operating frequency
  – Reactance

• Specified in terms of:
  – Dissipation Factor (DF)
  – Tanδ
  – Q-Factor

• Common DF values
  – X7R ➞ 1.0%
  – NP0 ➞ 0.1%

\[
\text{DF} = \tan\delta = \frac{\text{ESR}}{|X_C|}
\]

\[
\text{ESR} = \text{DF} \cdot |X_C| = \frac{\text{DF}}{2 \cdot \pi \cdot f_{\text{sw}} \cdot C}
\]

\[
Q = \frac{1}{\text{DF}} = \frac{1}{\tan\delta} = \frac{|X_C|}{\text{ESR}}
\]
Capacitor, Losses

- Total Capacitance needed is ~6500pF (~7nF)
- Total Reactance
- Total ESR

<table>
<thead>
<tr>
<th>Capacitance</th>
<th>Total Capacitors Required</th>
<th>Total Reactance ($X_C$ in $\Omega$)</th>
<th>ESR (Ω)</th>
</tr>
</thead>
<tbody>
<tr>
<td>220pF</td>
<td>30</td>
<td>51.1 $\Omega$</td>
<td>51 mΩ</td>
</tr>
<tr>
<td>470pF</td>
<td>14</td>
<td>51.2 $\Omega$</td>
<td>51 mΩ</td>
</tr>
<tr>
<td>1000pF</td>
<td>7</td>
<td>48.1 $\Omega$</td>
<td>48 mΩ</td>
</tr>
</tbody>
</table>

- Power loss per Capacitor

<table>
<thead>
<tr>
<th>Capacitance</th>
<th>220pF</th>
<th>470pF</th>
<th>1000pF</th>
</tr>
</thead>
<tbody>
<tr>
<td>ESR</td>
<td>1.53 $\Omega$</td>
<td>0.72 $\Omega$</td>
<td>0.34 $\Omega$</td>
</tr>
<tr>
<td>Current</td>
<td>0.333 A</td>
<td>0.714 A</td>
<td>1.43 A</td>
</tr>
<tr>
<td>Power</td>
<td>0.170 W</td>
<td>0.364 W</td>
<td>0.729 W</td>
</tr>
</tbody>
</table>

- Must have parallel caps to improve thermal stability
Power Device, Selection

• Devices need to provide low losses at 500kHz is a challenge

• Switching Losses: ZVS or ZCS reduces switching losses leaving conduction

• Conduction Losses: Modern MOSFETs achieve ultra low Rds_on

• Vishay Si7840DP has 15mOhm typical, and low switching transition time
The Loss Model

- Includes the parasitics
  - Trace losses
  - Power devices
  - Inductor AC resistance and core loss
  - Transformer AC resistance and core loss
  - Capacitor ESR
Revised Loss Model

Estimated Design Efficiency $\sim 83.5\%$
First Round of Testing

- Proved topology was capable of generating a low distortion sinewave output
First Round of Testing

- Initial testing of the first design did not meet the intended RF output power (max $P_o \sim 62$ Watts)

- Core losses are higher than expected
Design Improvements

• Improve core losses in the transformer by adding a small gap of (0.1mm)

• Change transformer turns ratio from 4 to 3 to allow 2-turns on the primary to increase the reactance from the magnetization inductance to improve load matching

<table>
<thead>
<tr>
<th>Primary Turns</th>
<th>2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Primary Inductance</td>
<td>1.8 uH</td>
</tr>
<tr>
<td>Secondary Turns</td>
<td>6</td>
</tr>
<tr>
<td>Secondary Inductance</td>
<td>8.12 uH</td>
</tr>
<tr>
<td>Turns Ratio</td>
<td>3</td>
</tr>
<tr>
<td>Core Gap</td>
<td>0.1 mm</td>
</tr>
</tbody>
</table>

• Change the series inductor to an air core type
  - Using Wheeler Equation

\[ L = \frac{0.8 \cdot r^2 \cdot N^2}{6r + 9l + 10d} \]

All in inches

- \( r \) = coil mean radius
- \( l \) = coil length
- \( d \) = depth of coil (OD - ID)
- \( N \) = number of turns

<table>
<thead>
<tr>
<th>Inductance</th>
<th>5.6 uH</th>
</tr>
</thead>
<tbody>
<tr>
<td>Outer Diameter</td>
<td>31.75 mm</td>
</tr>
<tr>
<td>Inner Diameter</td>
<td>12.70 mm</td>
</tr>
<tr>
<td>Overall Length</td>
<td>38.10 mm</td>
</tr>
<tr>
<td>Turns per Layer</td>
<td>9</td>
</tr>
<tr>
<td>Layers</td>
<td>3</td>
</tr>
</tbody>
</table>
Resonant Amplifier Final Design
The RF Gen Board
Enclosure

- For safety the RF Gen board was mounted in a enclosure and a fan added to ensure cooling until all testing could be completed

- Front

- Back
DC-DC Buck Stage Testing

- The output voltage of the DC-DC Buck is variable to control the RF output amplitude.
- The efficiency is a function of the output voltage.
- At 10V, full power the efficiency ~ 87%
• At 35V full power the efficiency ~95%
Overall Efficiency of Improved Design

Core Air, g=1mm, tx=2/6: Efficiency vs Load

- DC-DC Eff (Actual)
- RF stage Eff (Actual)
- Total Eff (Actual)

Efficiency (%) vs Load (Ohms)
RF Output Power

Core Air, g=1mm, tx=2/6: RF Power vs Load

- **RF Power (Target)**
- **RF Power (Actual)**

**Y-axis:** Power (Watts)

**X-axis:** Load (Ohms)
RF Output Voltage Limit

Core Air, g=1mm, tx=2/6: Output Voltage vs Load

Output Voltage (Volt pk-pk)

Load (Ohms)

V_{rf}
## Summary of Target Design

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Target</th>
<th>Actual Bench Test</th>
</tr>
</thead>
<tbody>
<tr>
<td>Input Voltage Range</td>
<td>42 to 60 Vdc</td>
<td>42 to 55 Vdc</td>
</tr>
<tr>
<td>Output Frequency at 50 Ohm</td>
<td>472kHz</td>
<td>473kHz</td>
</tr>
<tr>
<td>Frequency Variation</td>
<td>±23kHz</td>
<td>+20kHz –42kHz (ΔF = 62kHz)</td>
</tr>
<tr>
<td>Max output power</td>
<td>112 Watts at 20 Ohms</td>
<td>116 Watts at 20 Ohms</td>
</tr>
<tr>
<td>Output power derating</td>
<td>13 Watts at 500 Ohms</td>
<td>19.8 Watts at 500 Ohms</td>
</tr>
<tr>
<td>Output Load Impedance</td>
<td>20 to 500 Ohms</td>
<td>20 to 500 Ohms</td>
</tr>
<tr>
<td>Max output voltage at no load</td>
<td>250 Volts peak to peak</td>
<td>246 Volts peak to peak</td>
</tr>
<tr>
<td>Efficiency</td>
<td>&gt;80% at full power</td>
<td>72.7% at 116 Watts</td>
</tr>
<tr>
<td>Package size</td>
<td>77mm x 102mm x 51mm</td>
<td>127mm x 152.4mm x 63.5mm</td>
</tr>
</tbody>
</table>
                          (Volume 400 cm^3) | (Volume 1229.0 cm^3)      |
CSU RF Output High Voltage

- HV Transformer Design was based on other magnetics
  - High output voltage 1000 VRMS
  - High turns ratio 15

<table>
<thead>
<tr>
<th>Core material</th>
<th>Ferroxcube 3F35</th>
</tr>
</thead>
<tbody>
<tr>
<td>Form factor</td>
<td>Ferroxcube ETD34/17/11</td>
</tr>
<tr>
<td>Insulating Tape (between layers)</td>
<td>3M 1205 Tape</td>
</tr>
<tr>
<td>Turns Ratio</td>
<td>15</td>
</tr>
<tr>
<td>Primary Turns</td>
<td>4</td>
</tr>
<tr>
<td>Primary Wire</td>
<td>4 parallel strands of 24AWG ESSEX H Ultrashield Plus</td>
</tr>
<tr>
<td>Primary Inductance</td>
<td>3.6 uH</td>
</tr>
<tr>
<td>Secondary Turns</td>
<td>60</td>
</tr>
<tr>
<td>Secondary Wire</td>
<td>1 strand of 24AWG ESSEX H Ultrashield Plus</td>
</tr>
<tr>
<td>Secondary Inductance</td>
<td>1665 uH</td>
</tr>
<tr>
<td>Core Gap</td>
<td>0.1 mm</td>
</tr>
</tbody>
</table>
CSU RF Output High Voltage, Results
Gas Plasma

• Conditions Prior to Skin Penetration
CSU RF Output High Voltage, Results
Liquid Plasma

• Conditions: Inner body using Saline Solution
Future Work

• Add Switch Phase Detection for improved frequency tuning response and impedance control

• Redesign the RF stage for high voltage plasma version (Liquid and Gas) (*Hong Yao, CSU MS project, current*)

• Consider load dynamic RF matching in output stage for plasma for improved stability and efficiency (*Craig Power, CSU MS project, current*)

• Redesign the power supply section for reduced size (*Closely related work, Mike Schover, CSU MS project, current*)
  – 110Vac input
  – Battery
Switch Phase Detection

- Compares the switch voltage and switch current
- Outputs a voltage that represents the phase difference
- Using the Analog to Digital Converter (ADC) the software can adjust the frequency
• Based on simulations the concept could work
Plasma Version

• Design a version that is self-contained with ability of drive a plasma load directly (1-2 kV RMS)

• Eliminate the requirement of external High Voltage transformer

• Increase PCB spacing to meet the HV requirement

• Change the output current sense to have the proper isolation level (~3kV)
Dynamic Matching

- Use phase detection IC to sense phase shifts of output voltage and output current

- Adjust impedance matching network

- Load matching to achieve output maximum power transfer.
Redesign Input Power

- Eliminate the requirement of an external 48V power source.
- This will simplify the system to one box.
- Change the buck power source to a off-line topology

- For portable use in the field (emergency response services)
- Design the input source to be compatible with a battery
Acknowledgments

• Dr. Collins
  – Guidance, support, and motivation

• Covidien
  – Craig, Mark and Covidien for financial support

• Committee members (Dr. Chen, Dr. Sakurai, Dr. Siegel)
  – Support and flexibility allowing this final exam

• Dr. Koo, Sam Choi, Hong Yao
  – Assistance in testing, editing and proofing

• My Family
  – My wife and daughter for their patience and support
Questions?