Saber Tutorial
Quasi-resonant Flyback Converter Simulation

Alan Courtay
March 7, 2016
Agenda

• Quasi-Resonant Flyback Converter (AN1326)
  – Principles of Operation
    – Simulation vs. Measurement
• Accurate Datasheet-Driven Modeling
  – Controller Chip
  – MOSFET
  – Transformer
• Automated Verification
  – EMI
  – Loss / Efficiency
L6565-Based 50W QR ZVS Flyback

Vin: 50/60Hz, 88 to 264 Vac

Vout1: 105 V ± 5%
Iout1: 0.1 to 0.35 A
Vripple1: 1%

Vout2: 14 V ± 10%
Iout2: 0.1 to 1 A
Vripple2: 1%
L6565-Based 50W QR ZVS Flyback

Vin: 50/60Hz, 88 to 264 Vac

Vds

Llk+Lp

Lp&Cd

Cd

Vout1: 105 V ± 5%
lout1: 0.1 to 0.35 A
Vripple1: 1%

Vout2: 14 V ± 10%
lout2: 0.1 to 1 A
Vripple2: 1%

Power Stage

Discontinuous Conduction Mode
Peak Current Mode Control

Demagnetization
L6565-Based 50W QR ZVS Flyback

Vin: 50/60Hz, 88 to 264 Vac

Power Stage

Vds

Valley Switching

Vin

Currents

Ipeak

T_on

T_off

Vout1: 105 V ± 5%
Iout1: 0.1 to 0.35 A
Vripple1: 1%

Vout2: 14 V ± 10%
Iout2: 0.1 to 1 A
Vripple2: 1%
L6565-Based 50W QR ZVS Flyback

Vin: 50/60Hz, 88 to 264 Vac

Power Stage

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- Iout1: 0.1 to 0.35 A
- Vripple1: 1%

- Vout2: 14 V ± 10%
- Iout2: 0.1 to 1 A
- Vripple2: 1%

Power Stage

Vds

Skip Cycle

Vin

T_{on}

T_{off}

I_{peak}

T

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L6565-Based 50W QR ZVS Flyback

Vin: 50/60Hz, 88 to 264 Vac

Output Voltage Regulation Feedback

Vout1: 105 V ± 5%
Iout1: 0.1 to 0.35 A
Vripple1: 1%

Vout2: 14 V ± 10%
Iout2: 0.1 to 1 A
Vripple2: 1%
L6565-Based 50W QR ZVS Flyback
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Current Sense and Primary Voltage
Full Load, Vin = 100 V

Ch2: Q1 drain voltage
Ch3: current sense pin

- Tek Stop: 25.0MS/s
- 931 Accis

V = 100V
4µs
1V

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Current Sense and Primary Voltage
Full Load, $Vin = 380$ V

Ch2: Q1 drain voltage
Ch3: current sense pin
Current Sense and Primary Voltage
Half Load, $\text{Vin} = 100 \text{ V}$

- **Ch2**: Q1 drain voltage
- **Ch3**: current sense pin

**Current Sense**

- 100V
- 4µs

**Drain Voltage**

- 20V
- 4µs
Current Sense and Primary Voltage
Half Load, Vin = 380 V

Ch2: Q1 drain voltage
Ch3: current sense pin
Cycle Skipping / Frequency Foldback
Light Load, Vin = 300 V

Ch1: Q1 drain voltage
Ch2: 105 V output

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Current Sense and Primary Voltage
Standby, Vin = 380 V

TekStop: 250kS/s
15 Acq

Ch1: Q1 drain voltage
Ch2: current sense pin

Burst Mode

0.5V
100µs

100V

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Modeling Controller IC

L6565

vff  zcd  gd  cs  vcc  gnd

comp  inv

pc817

TL431

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Modeling Controller IC

L6565
Modeling Controller IC

L6565

Valley detection model with StateAMS tool

Blanking time model with TLU tool

Frequency foldback

Turn-on
Modeling Controller IC

L6565

Line voltage feedforward function implemented in MAST

Limits power capability at high line voltage

Turn-off
Modeling Power MOSFET
Modeling Power MOSFET

- DC Characteristics

Characterized Temperatures

<table>
<thead>
<tr>
<th>Temp1</th>
<th>Temp2</th>
</tr>
</thead>
<tbody>
<tr>
<td>25</td>
<td>75</td>
</tr>
</tbody>
</table>

Graph showing Id vs Vds with measured data at different temperatures.
Modeling Power MOSFET

- DC Characteristics
- Interelectrode Capacitances

\[ C(\text{pF}) \]

\[ f = 1 \text{ MHz} \]

\[ V_{GS} = 0 \text{V} \]

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>( C_{iss} )</td>
<td>1.122n</td>
</tr>
<tr>
<td>( C_{oss} )</td>
<td>1.933n</td>
</tr>
<tr>
<td>( C_{iis} )</td>
<td>1.004n</td>
</tr>
<tr>
<td>( C_{sos} )</td>
<td>0.973n</td>
</tr>
<tr>
<td>( C_{iss} )</td>
<td>1.737n</td>
</tr>
<tr>
<td>( C_{oss} )</td>
<td>2.447n</td>
</tr>
<tr>
<td>( C_{iis} )</td>
<td>312p</td>
</tr>
<tr>
<td>( C_{sos} )</td>
<td>500p</td>
</tr>
</tbody>
</table>

Profile: 0.45

Vds from -10 to 50 by 0.1
Modeling Power MOSFET

- DC Characteristics
- Interelectrode Capacitances
- Gate Charge Characteristic

![Graph showing DC Characteristics and Gate Charge Characteristics](image-url)

$V_{DS} = 540V$
$I_D = 7A$

<table>
<thead>
<tr>
<th>Temp (°C)</th>
<th>Vdd (V)</th>
<th>Vgs (V)</th>
<th>Iload (A)</th>
</tr>
</thead>
<tbody>
<tr>
<td>25</td>
<td>640</td>
<td>12</td>
<td>7</td>
</tr>
</tbody>
</table>

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Modeling Transformer
Modeling Transformer

- Ferrite Core 3C85
  - Hysteresis (major and minor BH loops)
  - Frequency dependent losses (hysteresis and eddy currents)
Modeling Transformer

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Modeling Transformer

• Ferrite Core 3C85
  – Hysteresis (major and minor BH loops)
  – Frequency dependent losses (hysteresis and eddy currents)
• Core geometry
  – Air gap
  – Lamination

![Transformer diagram]

![Modeling interface]

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Modeling Transformer

• Ferrite Core 3C85
  – Hysteresis (major and minor BH loops)
  – Frequency dependent losses (hysteresis and eddy currents)

• Core geometry
  – Air gap
  – Lamination

• Windings (Cauer - 1D Model)
  – Flux leakage
  – Frequency dependent loss (skin and proximity effects)
  – Winding capacitances
Modeling Transformer

- Ferrite Core 3C85
  - Hysteresis (major and minor BH loops)
  - Frequency dependent losses (hysteresis and eddy currents)
- Core geometry
  - Air gap
  - Lamination
- Windings (Cauer - 1D Model)
  - Flux leakage
  - Frequency dependent loss (skin and proximity effects)
  - Winding capacitances

<table>
<thead>
<tr>
<th>Core</th>
<th>ETD29/16/10, N67 Material or 3C85 or equivalent</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bobbin</td>
<td>Horizontal mounting, 14 pins</td>
</tr>
<tr>
<td>Leaksage inductance</td>
<td>~ 1 mm for an inductance 1-3 of 285 µH</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Pin Start/End</th>
<th>Winding Voltage</th>
<th>Wire</th>
<th>Turns</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Leakage inductance</td>
<td>-</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Winding</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Resistance</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Inductance</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Capacitance</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

![Graph and Simulation Tools](image)
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L6565-based 50W QR Flyback (ST AN1326)
L6565-based 50W QR Flyback (ST AN1326)
Experiment Editor Basic Tasks
Parallel Computing
<table>
<thead>
<tr>
<th>Task Label</th>
<th>Task Definition</th>
<th>Description</th>
<th>Task Status</th>
</tr>
</thead>
<tbody>
<tr>
<td>vary</td>
<td>vary-param flyback2_v_sin_v_sin1.amplitude</td>
<td></td>
<td>Complete</td>
</tr>
<tr>
<td>flyback2_v_sin_v_sin1.amplitude-d5</td>
<td></td>
<td></td>
<td>Complete</td>
</tr>
<tr>
<td>flyback2_v_sin_v_sin1.amplitude-50</td>
<td></td>
<td></td>
<td>Complete</td>
</tr>
<tr>
<td>flyback2_v_sin_v_sin1.amplitude-90</td>
<td></td>
<td></td>
<td>Complete</td>
</tr>
<tr>
<td>flyback2_v_sin_v_sin1.amplitude-110</td>
<td></td>
<td></td>
<td>Complete</td>
</tr>
<tr>
<td>flyback2_v_sin_v_sin1.amplitude-120</td>
<td></td>
<td></td>
<td>Complete</td>
</tr>
<tr>
<td>flyback2_v_sin_v_sin1.amplitude-135</td>
<td></td>
<td></td>
<td>Complete</td>
</tr>
<tr>
<td>flyback2_v_sin_v_sin1.amplitude-150</td>
<td></td>
<td></td>
<td>Complete</td>
</tr>
<tr>
<td>flyback2_v_sin_v_sin1.amplitude-155</td>
<td></td>
<td></td>
<td>Complete</td>
</tr>
<tr>
<td>flyback2_v_sin_v_sin1.amplitude-200</td>
<td></td>
<td></td>
<td>Complete</td>
</tr>
<tr>
<td>power_in</td>
<td>power_in = (mess1-mess2)*freq</td>
<td>58.148834386357</td>
<td>Complete</td>
</tr>
<tr>
<td>power_out</td>
<td>power_out = (mess2-mess1)*freq</td>
<td>50.741302140484</td>
<td>Complete</td>
</tr>
<tr>
<td>efficiency</td>
<td>efficiency = power_out / power_in</td>
<td>0.87056506827554</td>
<td>Complete</td>
</tr>
<tr>
<td>power_D1</td>
<td>power_D1 = (mess1-mess2)*freq</td>
<td>0.00949950039561</td>
<td>Complete</td>
</tr>
<tr>
<td>power_D2</td>
<td>power_D2 = (mess2-mess1)*freq</td>
<td>0.00854087361965</td>
<td>Complete</td>
</tr>
<tr>
<td>power_D3</td>
<td>power_D3 = (mess1-mess2)*freq</td>
<td>0.00854087361965</td>
<td>Complete</td>
</tr>
<tr>
<td>power_D4</td>
<td>power_D4 = (mess2-mess1)*freq</td>
<td>0.00854087361965</td>
<td>Complete</td>
</tr>
<tr>
<td>power_D5</td>
<td>power_D5 = (mess1-mess2)*freq</td>
<td>0.00854087361965</td>
<td>Complete</td>
</tr>
<tr>
<td>power_D6</td>
<td>power_D6 = (mess2-mess1)*freq</td>
<td>0.00854087361965</td>
<td>Complete</td>
</tr>
<tr>
<td>power_core</td>
<td>power_core = (mess1-mess2)*freq</td>
<td>0.98667631766666</td>
<td>Complete</td>
</tr>
<tr>
<td>power_windings</td>
<td>power_windings = (mess1-mess2)*freq</td>
<td>2.082004366526</td>
<td>Complete</td>
</tr>
<tr>
<td>power_model</td>
<td>power_model = (mess1-mess2)*freq</td>
<td>0.9931009794912</td>
<td>Complete</td>
</tr>
<tr>
<td>power_NTC</td>
<td>power_NTC = (mess1-mess2)*freq</td>
<td>1.183948375253</td>
<td>Complete</td>
</tr>
<tr>
<td>power_TL01</td>
<td>power_TL01 = (mess1-mess2)*freq</td>
<td>0.01402736555951</td>
<td>Complete</td>
</tr>
<tr>
<td>power_R1R2</td>
<td>power_R1R2 = (mess1-mess2)*freq</td>
<td>0.12769301658161</td>
<td>Complete</td>
</tr>
<tr>
<td>power_R2</td>
<td>power_R2 = (mess1-mess2)*freq</td>
<td>0.016633026952</td>
<td>Complete</td>
</tr>
</tbody>
</table>

**NOTE:** Restored :flyback2_v_sin_v_sin1:amplitude to its original initial value expression/association.
<table>
<thead>
<tr>
<th>Task Label</th>
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<th>Task Status</th>
</tr>
</thead>
<tbody>
<tr>
<td>power_in</td>
<td>power_in = (mess1+mess2)*freq</td>
<td>58.1488343883577</td>
<td>Complete</td>
</tr>
<tr>
<td>power_out</td>
<td>power_out = (mess1+mess2)*freq</td>
<td>50.7413094194584</td>
<td>Complete</td>
</tr>
<tr>
<td>efficiency</td>
<td>efficiency = power_out / power_in</td>
<td>0.937050503827594</td>
<td>Complete</td>
</tr>
<tr>
<td>power_D1</td>
<td>power_D1 = (mess1+mess2)*freq</td>
<td>528.9990236503724</td>
<td>Complete</td>
</tr>
<tr>
<td>power_D2</td>
<td>power_D2 = (mess1+mess2)*freq</td>
<td>0.0046149588003993</td>
<td>Complete</td>
</tr>
<tr>
<td>power_D3</td>
<td>power_D3 = (mess1+mess2)*freq</td>
<td>0.086049807619833</td>
<td>Complete</td>
</tr>
<tr>
<td>power_D4</td>
<td>power_D4 = (mess1+mess2)*freq</td>
<td>0.053816825659666</td>
<td>Complete</td>
</tr>
<tr>
<td>power_D5</td>
<td>power_D5 = (mess1+mess2)*freq</td>
<td>0.272138284175905</td>
<td>Complete</td>
</tr>
<tr>
<td>power_D6</td>
<td>power_D6 = (mess1+mess2)*freq</td>
<td>0.700739731617224</td>
<td>Complete</td>
</tr>
<tr>
<td>power_core</td>
<td>power_core = (mess1+mess2)*freq</td>
<td>0.986675616796666</td>
<td>Complete</td>
</tr>
<tr>
<td>power_windings</td>
<td>power_windings = (mess1+mess2)*freq</td>
<td>2.0869034062562</td>
<td>Complete</td>
</tr>
<tr>
<td>power_model</td>
<td>power_model = (mess1+mess2)*freq</td>
<td>0.995519697949190</td>
<td>Complete</td>
</tr>
<tr>
<td>power_NTC</td>
<td>power_NTC = (mess1+mess2)*freq</td>
<td>11.8033820752537</td>
<td>Complete</td>
</tr>
<tr>
<td>power_TLC1</td>
<td>power_TLC1 = (mess1+mess2)*freq</td>
<td>0.016274353535355</td>
<td>Complete</td>
</tr>
<tr>
<td>power_R1</td>
<td>power_R1 = (mess1+mess2)*freq</td>
<td>0.127684126816107</td>
<td>Complete</td>
</tr>
<tr>
<td>power_R2</td>
<td>power_R2 = (mess1+mess2)*freq</td>
<td>0.018663220592</td>
<td>Complete</td>
</tr>
<tr>
<td>power_R3</td>
<td>power_R3 = (mess1+mess2)*freq</td>
<td>0.018663220592</td>
<td>Complete</td>
</tr>
<tr>
<td>power_R4</td>
<td>power_R4 = (mess1+mess2)*freq</td>
<td>0.018663220592</td>
<td>Complete</td>
</tr>
</tbody>
</table>

Most dissipative components:
- power_in
- power_out
- efficiency
- power_D1
- power_D2
- power_D3
- power_D4
- power_D5
- power_core
- power_windings
- power_model
- power_NTC
- power_TLC1
- power_R1
- power_R2
- power_R3
- power_R4
Conduction Losses

Switching Losses
**Conduction Losses**

**Switching Losses**

Rac = 35kΩ added across primary to account for air gap fringing field losses.

NTC thermistor adjusted to 2.8Ω.
NTC thermistor adjusted to 2.8Ω

Rac = 35kΩ added across primary to account for air gap fringing field losses
Conclusion

• High fidelity models characterized from datasheets
• Automated design verification / regression testing over broad operating conditions
  – Experiment Analyzer
  – Fault Injection
  – Worst Case Analysis / Extreme Value Analysis
  – Statistical variations (Monte Carlo)
• Scalable solution
  – Capacity for large designs (network of power converters)
  – User or site (company wide) model library management
  – Distributed/grid iterative analysis (parametric Vary, Monte-Carlo, Worst-Case Analysis, Fault)
Thank You

• Flyback design available on Synopsys Forum
• Improved IGBT Tool in 2016.03

Thank you to Sophia LI, Min ZHANG and Balaji EMANDI for their contributions.
Special thanks to Claudio ADRAGNA and Giovanni GRITTI from ST for their valuable feedback.