TI Live! INDIA AUTOMOTIVE SEMINAR
BING LU

ISOLATED BIAS SUPPLY SOLUTIONS FOR ISOLATED GATE DRIVERS
Agenda

• Inverter and isolated gate driver bias supply architectures
• Different ways of creating isolated bias supply
  – Control method
  – Topology
  – Transformer
• LLC based open-loop isolated bias supply
  – Operation principles
  – Voltage regulation
• Isolated bias supply with integrated transformers
  – Power density improvement
  – Voltage regulation
Inverters in different applications

- **Traction inverter**
- **Motor drive**
- **On-board charger**
- **UPS**
Example: inverter isolation boundaries

How to bias the isolated drivers?
Different gate driver architectures

**Centralized**

- GD1
- GD3
- GD5
- GD2
- GD4
- GD6

**Semi-distributed**

- GD1
- GD3
- GD5

- GD2
- GD4
- GD6

**Distributed**

- GD1
- GD3
- GD5

- GD2
- GD4
- GD6

- GD1
- GD3
- GD5

- GD2
- GD4
- GD6

• Centralized system has lowest cost, but heavy and difficult to manage fault
• Distributed systems distribute the weight and fault, but more expensive
• Semi-distributed is somewhere in the middle
Output voltage control

**Close loop**
- Secondary side feedback
  - Well regulated output
  - No need pre-regulator
  - More components
  - Less reliable due to the opto coupler

**Close loop**
- Primary side feedback
  - Semi regulated output
    - Determined by cross regulation
  - No need pre-regulator
  - Noise sensitive due to the output voltage sampling method

**Open loop**
- No feedback
  - No control loop, robust operation
  - Less noise
    - Coupling only through the transformer
  - Unregulated output, need pre-regulator

Open-loop control provides a robust solution
Topologies used for isolated bias supply

Flyback

Push-pull

LLC
Transformer parameter impacts to system EMI

- High dv/dt couples through transformer parasitic capacitor to the primary side
- Higher EMI noise
- Extra loss
- More noise to the controller, CMTI issue
- It gets worse with SiC or GaN devices with higher dv/dt
Transformer structure: less parasitic capacitance

**Typical two-winding PSR Flyback transformer**

The capacitance can be reduced by increasing the insulator thickness
Less effective due to the large surface area

**Typical LLC transformer**

Split bobbin reduces the capacitance by reducing the surface area and increasing the distance
Much smaller capacitance can be achieved

Increasing the distance reduces the capacitance while increasing the leakage inductance
How topologies respond to leakage inductance

Flyback

- Leakage energy can’t be transferred to secondary side
- Leakage causes
  - More EMI noise due to ringing
  - More loss
  - More device stress
- Leakage needs to be minimized

Push-pull

LLC

- Leakage is part of resonant circuit
- Leakage energy is fully recovered
- No extra ringing caused by the leakage
- No limitations on the leakage inductance
LLC converter

- At resonant frequency, the impedance of resonant tank is equal to zero, input and output is shorted through the transformer. Fixed frequency open-loop control is possible.
- The leakage inductance of the transformer can be used as the resonant inductor.

\[ f_0 = \frac{1}{2\pi \sqrt{L_r C_r}} \]

\[ Q_e = \frac{\sqrt{L_r / C_r}}{R_e} \]

\[ R_e = \frac{8n^2}{\pi^2} R_L \]
Transformers for isolated bias supply

<table>
<thead>
<tr>
<th>LLC transformer</th>
<th>Push-pull transformer</th>
<th>Three-winding flyback</th>
<th>Two-winding PSR flyback</th>
</tr>
</thead>
<tbody>
<tr>
<td>Core</td>
<td>Bobbin</td>
<td>Core</td>
<td>Bobbin</td>
</tr>
<tr>
<td>Split bobbin</td>
<td>Secondary</td>
<td>Pry1* Pry2* Sec1* Sec2*</td>
<td>Secondary</td>
</tr>
<tr>
<td>Secondary</td>
<td>Primary</td>
<td>Secondary</td>
<td>Primary</td>
</tr>
</tbody>
</table>

- **C\textsubscript{Pri-Sec}**:
  - LLC: <2pF
  - Push-pull: ~10 pF
  - Three-winding flyback: ~20 pF
  - Two-winding PSR flyback: ~20 pF

- **CMTI**:
  - LLC: >150V/ns
  - Push-pull: Worse than LLC
  - Three-winding flyback: Worse than LLC
  - Two-winding PSR flyback: Much worse than LLC

- **Cost**:
  - LLC: 1X
  - Push-pull: >1.15
  - Three-winding flyback: >1.3X
  - Two-winding PSR flyback: >1.18X

- **EMI**:
  - LLC: Best
  - Push-pull: Good
  - Three-winding flyback: Poor
  - Two-winding PSR flyback: Poor

- **Regulation**:
  - LLC: Good
  - Push-pull: Good
  - Three-winding flyback: Better
  - Two-winding PSR flyback: Best

**LLC converter provides an order of amplitude capacitance reduction**
Open-loop LLC voltage regulation

\[ v_o \approx \frac{v_{in}}{n} - \frac{\pi^2}{2} \left( \frac{R_{SW}}{n^2} + \frac{R_P}{n^2} + R_S \right) \cdot I_O - 2v_f \]

- The voltage regulation is determined by transformer turns ratio and resistive loss, as well as the diode drop
- It is critical to keep the resistive loss low to get best load regulation
Split single output voltage into dual outputs

**Zener split**
- Lowers cost
- Unregulated outputs

**Shunt Regulator**
- Higher cost
- Regulated negative output
- Unregulated positive output

**Shunt Regulator & Linear regulator**
- Highest cost
- Regulated output
UCC25800-Q1
Low-cost LLC transformer driver with high performance

Features

▪ Operation from 9 V to 34 V (40 V Abs Max)
▪ 6 W from 24-V input, Up to 10 W from 34-V input
▪ Integrated half-bridge MOSFETs
▪ Programmable fixed switching frequency up to 1.2 MHz
  – 1.2 MHz default, resistor settable 100 kHz – 1 MHz
  – Frequency accuracy +/-6% maximum over temperature
  – External SYNC function
▪ Drive multiple transformers with one UCC25800-Q1
▪ Automatic dead time adjustment with programmable maximum
▪ Integrated soft-start
▪ Disable pin with fault code output
▪ Two-level over current protection
  – Programmable via external resistor
  – UCC25800L is latched after over current
  – UCC25800R is retry after over current
▪ Over Temperature Protection
  – 160°C Junction
  – 10°C Hysteresis
▪ AEC Q100 Qualified

Benefits

▪ Low common mode noise due to minimal interwinding capacitance in transformer
▪ Simple design, highly integrated, no bootstrap capacitor
▪ High switching frequency for smaller size and more robustness

[Disclaimer: Specs, features & pinouts subject to change without prior notice.]
UCC25800-Q1 measurement data

UCC25800 EVM with LM5156 pre-regulator

<table>
<thead>
<tr>
<th>PARAMETER</th>
<th>SPECIFICATIONS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Input voltage range</td>
<td>6V – 26V</td>
</tr>
<tr>
<td>Output voltage and current</td>
<td>+18V / -5V</td>
</tr>
<tr>
<td>Switching frequency</td>
<td>2.2MHz and 500 kHz</td>
</tr>
<tr>
<td>Isolation</td>
<td>Yes, 2500 VAC (1 sec)</td>
</tr>
<tr>
<td>Topology</td>
<td>SEPIC + Open loop LLC transformer driver</td>
</tr>
</tbody>
</table>

Predictable startup of +/- rails

1% Load regulation

Surpasses CISPR 25 class 5 EMI standard

Pass - LLC Board Only with Filter
EMI noise performance comparison

5-V push-pull

24-V LLC

24-V Flyback

LLC has much lower high frequency EMI noise, which is the most difficult to filter out

*No EMI filter added on any topologies
CMTI performance of UCC25800 based LLC

Operation is not affected by >150 V/ns CMTI
Transformer design considerations

- Transformer design is simple
  - Two windings
  - Turns ratio is roughly the voltage ratio between the input and output voltage (plus the diode drop)
  - Square voltage on primary side, setting up the volt-second rating
  - Lowest Rac possible
  - No airgap

- Once the transformer is made, measure the leakage inductance from secondary side
  - Short the primary side while measuring

- Match the leakage inductance with resonant capacitor

<table>
<thead>
<tr>
<th>Part number (Wurth)</th>
<th>Turn ratio</th>
<th>Leakage inductance</th>
<th>Input / Output</th>
</tr>
</thead>
<tbody>
<tr>
<td>750319331</td>
<td>1:1</td>
<td>1.4 uH</td>
<td>24 V/24 V</td>
</tr>
<tr>
<td>750319177</td>
<td>1.67:1</td>
<td>1.48 uH</td>
<td>15 V/24 V</td>
</tr>
<tr>
<td>750319177</td>
<td>1:1.67</td>
<td>0.53 uH</td>
<td>24 V/15 V</td>
</tr>
</tbody>
</table>
How to further simplify the design

UCC25800-Q1 based open-loop LLC

UCC14240-Q1
1.5-W, high-efficiency, 3-kVRMS isolated DC/DC converter
Gate driver voltage accuracy requirement

Gate voltage effect on $R_{DS(ON)}$ sensitivity

![Normalized $R_{DS(ON)}$ vs Gate Voltage (V)]

$R_{DS(ON)}$ sensitivity increases with increasing gate voltage.

Conduction Loss = $I_{RMS}^2 \times R_{DS(ON)}$

Gate voltage effect on over-current detection

$V_{GS}$ change affects $I_{OC}$ correlation with $V_{CE(DESAT)}$ or $V_{DS(DESAT)}$ setting.

<table>
<thead>
<tr>
<th>Positive rail ($V_p$)</th>
<th>Si MOSFET</th>
<th>SiC MOSFET</th>
<th>IGBT</th>
</tr>
</thead>
<tbody>
<tr>
<td>+12V, +15V</td>
<td>+18V, +20V (5%, 3%, 1%)</td>
<td>+15V, +18V</td>
<td></td>
</tr>
<tr>
<td>Negative rail ($V_n$)</td>
<td>0V</td>
<td>-5V, -4V, -3V</td>
<td>-8V or 0V</td>
</tr>
</tbody>
</table>

Tight bias voltage regulation improves efficiency and OCP accuracy.
Isolated DC-DC module with integrated transformer
Technology shift for isolated gate driver bias supplies

Decades of **bulky transformers** …

- Bulky – prone to vibrations
- High radiated EMI
- Large footprint & height
- Difficult to design

![Bulky XFMR](image)

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Introducing the **UCC14240-Q1**

- 1.5W high-efficiency isolated DC/DC power supply
- Industry’s smallest, most accurate & easiest-to-use
- Proprietary integrated transformer technology
- No bulky, noisy transformers

![Flyback](image)

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2X smaller PCB area, lower BoM

![UCC14240-Q1](image)

---

2X lower height

![External](image)

---

7.5mm Height

3.5mm Height
TI integrated gate drive bias supply
Can be configured as two outputs or single output

**Two Outputs: \(V_{\text{POSITIVE}} \text{ & } V_{\text{NEGATIVE}}\)**

- \(\text{VIN} = 24\,\text{V or 12\,\text{V}}\)
- \(\text{VOUT} = \text{Both Adjustable} \leq 1.3\% \text{ accuracy}\)

- Higher inverter efficiency
- More accurate inverter current limit

**Single Output: \(V_{\text{POSITIVE}}\)**

- \(\text{VIN} = 24\,\text{V or 12\,\text{V}}\)
- \(\text{VOUT} = \text{Adjustable} \leq 1.3\% \text{ accuracy}\)

- Higher inverter efficiency
- More accurate inverter current limit

[Disclaimer: Specs, features & pinouts subject to change without prior notice.]
UCC14240-Q1 Best-in-class regulation

- 1.3% regulation over -40°C to 150°C
- No need post regulator
- Programmable positive and negative rail outputs

R1 & R2 control the VoutΔ (18-25V)

R3 & R4 control the negative and the positive voltages

Compact PCB Implementation

38mm
55mm
UCC14240-Q1
3.55 mm height dual output gate drive bias w/ integrated XFMR

Features
- Isolated power module with integrated transformer
- 3.55 mm height, 12.8 mm x 10.3 mm with leads (8mm creepage)
- 1.5-W output power at Ta = 105°C
- Input voltage range
  - 24V nominal
  - 21V – 27V, 32V Abs,max
- Dual adjustable output voltages
  - VDD to VEE Range 18 V to 25 V, ≤ 1.3% accuracy
  - COM to VEE Range 2.5 V to VDD, ≤ 1.3% accuracy
  - ≤ 1.3% Accuracy -40°C to 150°C
- Isolated DCDC for driving: IGBTs, SiC FETs, Si FETs, sys rails
- 3.5pF primary-to-secondary capacitance with low emissions
- Wide temperature range:
  - Tj: -40 to 150°C
  - Ta: -40 to 125°C
- UVLO, OVLO, PG, soft-start, short-circuit, power-Limit, and over temperature protection, CMTI > 150kV/us
- Basic isolation
  - 3kVrms (60s)
  - 1.2kVpk working
  - 5kV surge
- AEC-Q100 auto grade

Benefits
- Integrated solution enables smaller BOM, reduced board space and helps with easier system certification
- High accuracy to reduce size of IGBTs / SiC switches
- Soft start enables minimal overshoot current,
- Low EMI, high CMTI, high isolation voltage

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# UCC14240-Q1 Total Solution Comparison

<table>
<thead>
<tr>
<th>Architecture</th>
<th>Total PCB Area</th>
<th>Maximum Height</th>
<th>Vin / Power</th>
<th>Cpri-sec</th>
</tr>
</thead>
<tbody>
<tr>
<td>Integrated Transformer UCC14240</td>
<td>220 mm²</td>
<td>3.55 mm</td>
<td>21V – 27V 1.5W at 105°C</td>
<td>3.5pF</td>
</tr>
<tr>
<td>LLC Resonant UCC25800</td>
<td>525 mm²</td>
<td>9 mm</td>
<td>9V – 34V &lt; 10W (Centralized Architecture)</td>
<td>&lt; 1.5pF</td>
</tr>
<tr>
<td>Push-Pull SN6505</td>
<td>550 mm²</td>
<td>8 mm</td>
<td>2.25V – 5.5V &lt; 5W</td>
<td>7pF</td>
</tr>
<tr>
<td>Flyback LM(2)5180</td>
<td>600 mm²</td>
<td>13 mm</td>
<td>4.5V – 65V &gt; 10W</td>
<td>~20pF</td>
</tr>
<tr>
<td>Half Bridge UCC2813-Q1</td>
<td>560 mm²</td>
<td>10 mm</td>
<td>Controller &gt;10W</td>
<td>~20pF</td>
</tr>
</tbody>
</table>

**Note:** The table compares various architectures and their specifications for total PCB area, maximum height, input voltage (Vin), power, and coupling capacitance (Cpri-sec). The specifications are categorized into Integrated Transformer, LLC Resonant, Push-Pull, and Flyback architectures, with each subcategory detailing specific performance parameters.
## UCC14240-Q1 measurement data

### UCC14240 EVM

- **Small Area**
- **Low Height**

### PARAMETER | SPECIFICATIONS
--- | ---
Input voltage range | 21 V – 27 V
Dual Output voltage | +25 V / -5 V (programmable)
Regulation | < 1.3% accuracy
Isolation | Basic, 3k Vrms

### Soft startup of +/- rails

- VPOS = 15V
- VNEG = -5V
- PG = PowerGood Active Low

### < 1% load regulation

- **UCC14240 (VIN=24V, VISO=20V)**

### 60% peak efficiency

- **UCC14240 (VIN=24V, VISO=25V)**

### Cool 2-W out

- FLIR Image: 67.3°C
Summary

- Isolated bias supply is needed for biasing the isolated gate drivers in the inverters

- The open loop LLC converter provides a simple, robust solution
  - Less EMI
  - High CMTI
  - Good voltage regulation
  - Multiple output capability

- Integrated transformer solution provides
  - Highest level of integration, minimum external components
  - Highest power density, lowest profile
  - Best-in-class regulation, no post regulator needed
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