HIGH VOLTAGE SEMINAR

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HIGH VOLTAGE CONTROLLERS

ACHIEVING HIGH POWER DENSITY AND ULTRA LOW STANDBY POWER IN FLYBACK CONVERTERS
Agenda

• Basic PSR flyback operation/problems and issues
• Wake-up monitoring (UCC24650) with PSR sampling initiation (UCC28730)
  • Speeds up transient response
  • Greatly reduces output capacitance ($\approx C_{OUT}/7$)
  • Can meet zero power ($< 5 \text{ mw}$)
• Device feature set
• Design tips and tricks
• Questions
Typical Primary Side Regulation (PSR)

➢ Uses $N_A/N_S$ Turns ratio to sample $V_{OUT}$
  ✓ Control Reflected Output Voltage ($V_{OUT}$)
    • Sampled during rectifier diode conduction @ Knee
    • Removes the need of TL431 feedback
      o Saves $\text{$$$$}$ and reduces standby power

\[
(V_{OUT} + V_F + I_S R_S) \frac{N_A}{N_S} \quad - \quad (V_{BLK}) \frac{N_A}{N_P}
\]
Uses FM, AM ($I_{PP}$), FM modulation to control duty cycle

- Controller Samples Auxiliary Winding ($V_A$) to Adjust Duty cycle
  - While Energy is being delivered to secondary ($tc$) when $D_G$ is conducting
- Frequency Typically Varies from 1 kHz to 100 kHz

$$D = \frac{t_{ON}}{t_{ON} + t_C + t_D}$$
Negative side of PSR regulation

- This control scheme has a slow transient response
- When the Converter is Idle at $f_{\text{min}} = 1\,\text{kHz}$
  - Output is sampled and the Duty cycle is adjusted once every 1 ms.
  - The output capacitor ($C_{\text{OUT1}}$) must be sized to handle load transients

\[
C_{\text{OUT1}} \geq \frac{I_{\text{MAX}}}{dV \times f_{\text{min}}}
\]
Improving the load transient response with the UCC28730

- Wake-up monitoring (UCC24650) with PSR sampling initiation (UCC28730) for fast transient response.
  - UCC28730 PSR with output sampling initiation
    - Has all the features of traditional PSR controller
    - Can operate down to 32 Hz to meet < 5 mW Standby power
  - UCC24650 Secondary side wake-up monitoring
    - Monitors $V_{OUT}$ and will activate PSR sampling if $V_{OUT}$ drops out of regulation.
UCC24650 performance advantage

- UCC24650 Monitors $V_{OUT}$
  - If $V_{OUT} < 0.97 \times V_{OUT1}$
    - The secondary winding is shorted
      - 1us every 30 us with a current-limited switch

- UCC28730
  - Monitors the auxiliary winding (VA) during the deadtime
    - If a + pulse is observed
      - It Triggers PSR Sampling
        » Gate drive initiates a few sample pulses
          » $V_{OUT}$ is sampled
          » The controller quickly responds
            » Adjusts $I_{PP}$, frequency and Duty cycle
            » Recovers and Maintains $V_{OUT}$
Faster transient response with wake-up

- Reduces the amount of \( C_{OUT} \)
- \( C_{OUT} \) needs to be sized for
  - Output transients (dV) and the V loop for stability

\[
\begin{align*}
C_{OUT\_No\_Wakeup} & \geq \frac{100 \times I_{MAX}}{V_{OUT} \times f_{max}} \\
C_{OUT} & \geq \frac{I_{MAX}}{dV \times f_{max}} \times 10
\end{align*}
\]
How much is $C_{OUT}$ reduced with wake-up?

- Typical design
  - $f_{\text{min}} = 1$ kHz
  - $f_{\text{max}} = 80$ kHz

- Using a design with Wake-up
  - $C_{OUT}$ is reduced by a factor of 6.5
  - Output C with Wake-up ($C_{OUT2}$)
  - Output C without Wake-up ($C_{OUT1}$)

\begin{align*}
  C_{OUT1} & \geq \frac{I_{\text{MAX}}}{dV \times f_{\text{min}}} \\
  C_{OUT2} & \geq \frac{I_{\text{MAX}}}{dV \times f_{\text{max}} / 10} \\
  C_{OUT2} & = 10 \times \frac{C_{OUT1} \times f_{\text{min}}}{f_{\text{max}}} = \frac{C_{OUT1}}{6.5}
\end{align*}
Reducing $C_{OUT}$

- Increases design’s power density
- Enables the design to operate at higher frequencies
- Reduces the cost of the design

\[
C_{OUT1} \geq \frac{I_{MAX}}{dV \times f_{min}}
\]

\[
C_{OUT2} \geq \frac{I_{MAX}}{dV \times f_{max}}
\]

\[
C_{OUT2} = 10 \times \frac{C_{OUT1} f_{min}}{f_{max}} = \frac{C_{OUT1}}{6.5}
\]
Transient response with and without wake-up

- 5 V/10 W Design was evaluated, \( f = 1.25 \text{ kHz} \) to 80 kHz
- The design was tested with a full load transient step (0 to 2A)
- Without wake-up, controller could not sample \( t_{\text{wait}} \) \( V_{\text{OUT}} \) for 600us, \( V_{\text{OUT}} \) drooped 3V 😞
  - \( t_{\text{wait}} \) could have been as long 800 us
- With wake-up, controller responded quickly no waiting, \( V_{\text{OUT}} \) only drooped 0.4v 😊
UCC24650 200-V wake-up monitor for fast transient PSR

1 Features
- Enables Excellent Load Transient Performance and Zero Standby Power
- Enables Smallest Output Capacitor for Tight ΔV_{OUT}
- No External Components Required
- <50 μA Device Current Consumption (Typical)
- 5-V to 28-V Output Monitoring Capability
- 3% Voltage Droop Detection (Patent Pending)
- 200-V Wake-Up Switch
- Enables and Disables SR Controller, Relay Control, or Other Secondary Circuits
- SOT-23 5-Pin Package

2 Applications
- <5-mW Zero-Power Standby Applications
- Adapters and Chargers for Consumer Electronics
  - Smart Phones, Tablets, Set-Top Box
- TV and Monitor Power Supplies
- Home Appliance SMPS
  - Refrigerator, Washing Machine, Air Conditioners
- Industrial Power Supplies for Lighting and Home Automation

Note: No opto feedback required
UCC28730 zero-power standby PSR flyback controller with CVCC and wake-up monitoring

1 Features
- Enables Zero-Power (<5 mW) Standby Consumption
- Smart Wake-Up Detection Enables Smallest Output Capacitance
- Primary-Side Regulation (PSR) Eliminates Optocoupler
- ±5% Voltage Regulation and Current Regulation Across Line and Load
- 700-V Start-up Switch
- 83-kHz Maximum Switching Frequency Enables Low Stand-by Power Charger Designs
- Resonant-Ring Valley-Switching Operation for Highest Overall Efficiency
- Frequency-Dither to Ease EMI Compliance
- Clamped Gate-Drive Output for MOSFET
- Over-Voltage, Low-Line, and Over-Current Protection Functions
- Programmable Cable Compensation
- SOIC-7 Package

2 Applications
- Adapters and Chargers for Smart Phones, Tablets, and Other Consumer Electronics
- TV and Monitor Power Supplies
- SMPS for Home Appliances and Industrial Automation
- Standby and Auxiliary Power Supplies

Simplified Application Schematic
UCC28730 Protection/fault activation

• Over Voltage Protection (OVP)
  – \((N_S/N_A) \times (4.62V/R_{S2}) \times (R_{S1}+R_{S2})-V_D\)

• Over Current Protection (I_{OCP}) \(V_{RCS} = 1.5\)V
  – \(I_{OCP}=1.5V/R_{CS}\)
    • Nominal Peak \(V_{RCS} = 0.74\)V

• Input Under Voltage Protection (UVLO)
  – \(V_{IN} > (N_P/N_A) \times (225uA \times R_{S1})\) to startup
  – \(V_{IN} < (N_P/N_A) \times (80uA \times R_{S1})\) to shutdown

• Thermal Shut Down (TSD = 165 C)
• All faults stop switching and reactivate soft start
VDD charged through HV Input:
- 3 small gate driver pulses are initiated @ UVLO_{ON}
- I_{PP} controlled to 1/3 max at startup
- If fault is detected UVLO/soft start initiated
- Will retry at UVLO_{ON}
Startup with input under voltage fault

➢ At UVLO\textsubscript{ON} three gate drive pulse are initiated:
  ▪ CS peak is controlled to 1/3 max (245 mV)
  ▪ Input UVLO detected UVLO restart is initiated
Startup with no faults

➢ At UVLO_{ON} three gate drive pulse are initiated:
  ▪ CS peak is controlled to 1/3 max (245 mV)
  ▪ No Faults have been detected so supply starts switching
  ▪ After 3\textsuperscript{rd} initiated pulse I_{PP} is controlled to maximum threshold
    • (CS Controlled to 740mV)
UCC28730 zero power: reducing $f_{SW}$

- Control Law
  - Reduces $f_{SW}$ @ Standby (32 Hz minimum)
  - Enables
    - Low bias current (50uA)
    - $P_{IN} < 5mW$ at Standby
At max frequency converter is close to critical conduction

When DRV turns off OFF, VS looks for + transition and activates a VS blanking delay ($t_B$)
  - Prevents false OVP from leakage spike ($T_{LK\_RESET}$)
  - $t_B$ adjusts with loading
    - $V_{CS} = 0.74\text{V}$, $t_B = 2.25\ \mu\text{s}$; $V_{CS} = 0.245\text{V}$, $t_B = 750\ \text{nS}$
➢ After $t_B$ times out
➢ VS sampling starts ($t_S$) detection for OVP and output control
➢ During $t_S$ the VS pin is continuously sampled
   ▪ Will hold the last VS value sampled before LC tank ($t_R$) of switch node (M1 drain)
      ▪ This VS value is used to control the output
         • Helps remove errors caused by aux ringing
         • Ringing after delay needs to be $< 100$ mV p-p
After the controller has sampled the output at VS

- The switch node and aux winding will LC ring ($t_R$)
- The controller is looking for 0V transition of the Aux winding
  - When this occurs an internal timer/delay is triggered ($t_D$)
  - Once $t_D$ has timed out DRV will turn back on
    - This added delay allows valley switching
Device timing/control (FM)

- $V_{E/A}$ 3.55V to 5V, $V_{CS} = 0.74V$
  - Fixed $I_{PP}$ set at Max
  - A delay is added/adjusted ($t_{EP}$) to adjust D/frequency ($28 \text{ kHz} < 83 \text{ kHz}$)
  - Controller will not turn on M1 until VS zero is detected and $t_D$ has timed out (150ns)
    - This achieves valley switching deep into DCM

$$D = \frac{t_{ON}}{t_{ON} + t_B + t_S + t_{EP} + t_R + t_D}$$

- 0V
- 0A
Device timing/control (AM)

- $V_{E/A}$ 2.2V to 3.35V, $V_{CS} = 0.74V$ to 0.245V
  - Converter is operating deeper into DCM
  - Frequency is Fixed 28 kHz (Excluding Dither)
  - Duty Cycle is Controlled by Adjusting CS amplitude (AM) from $I_{PP}$ to $1/3 I_{PP}$
    - Was done to remove audible noise as load and $f$ decrease

\[ D = \frac{t_{ON}}{t_{ON} + t_{B} + t_{S} + t_{EP} + t_{R} + t_{D}} \]
**Device timing/sensing (FM)**

- $V_{E/A} = 1.3\text{V to } 2.2\text{V}$, $V_{CS} = 0.245\text{ V}$
  - Duty cycle is controlled by adjusting $t_{EP}$ (VCO/fixed peak current again)
  - Frequency is adjusted from 28 kHz down to 1.92 kHz depending on E/A out
  - $I_{PP}$ is fixed to $1/3 I_{PP\ MAX}$

\[ D = \frac{t_{ON}}{t_{ON} + t_B + t_S + t_{EP} + t_R + t_D} \]
Device timing/sensing (FM)

- VE/A 0.75 V to 1.3 V, \( V_{\text{RCS}} = 0.245 \text{ V} \)
  - Frequency shifts to lower operating level as load gets lighter

\[ D = \frac{t_{\text{ON}}}{t_{\text{ON}} + t_B + t_S + t_{\text{EP}} + t_R + t_D} \]
Device timing/sensing (FM)

➢ VE/A 0 V to 0.75 V, \( V_{RCS} = 0.245 \) V
  - Frequency bottoms out at 32 Hz

\[
D = \frac{t_{ON}}{t_{ON} + t_B + t_S + t_{EP} + t_R + t_D}
\]
System EMI reduction evaluation

- EMI comparison with and without dithering
  - Charger at 5V/1A: Vout return connected to earth
  - 2-5 dB reduction with EMI jittering scheme

![UCC28730 Conducted EMI Comparison](chart.png)
Frequency dithering affects output ripple

- Frequency jitter does cause a small amount of low frequency output ripple
  - Still meets USB specifications
  - CH2 = V_{OUT}
**$R_{LC}$ offset CS adjustment**

- Adds offset to the CS signal
  - Provides Some VFF
  - Provides an adjustment to reduce $I_{pp}$ over shoot
    - Caused by FET turnoff delays

$$R_{LC} = \frac{K_{LC} \times R_{S1} \times R_{CS} \times t_d \times N_{PA}}{L_p}$$
Design tips and recommendations

➢ VS Pin Recommendations

- No filtering/high impedance pin/noise sensitive
- Don’t probe the VS pin directly with a scope probe
  - Can estimate behavior at this pin from $D_E$
Design tips and recommendations

➢ CS pin recommendations
  ▪ Device has 225 ns of leading edge blanking
  ▪ Filtering should not be needed on the CS pin
    - If cap is added to CS input, RC delay will affect value of $R_{LC}$
➢ Leave place for a snubber on the output
   ▪ You may or may not need it
   ▪ Excessive ringing on VS pin could cause misbehavior
Transformer calculations

➢ T1 primary inductance ($L_{PM}$) set by $f_{\text{max}}$
  ▪ $f_{\text{max}}$ target 38 kHz to 76 kHz

\[
\frac{N_P}{N_S} = \sqrt{\frac{L_{PM}}{L_{SM}}}
\]

\[I_{PP} = \text{Peak T1 Primary } I_P\]

\[L_{PM} = \frac{2 \times P_{OUT}}{\eta I_{PP}^2 \times f_{\text{max}}}\]
Transformer turns ratio \( \frac{N_P}{N_S} \)

\[ D_{\text{MAX}} = \frac{t_{\text{ON}}}{T_{\text{SW}}} \]

\[ D_{\text{MAG}} = \frac{t_{DM}}{T_{SW}} \quad D_{\text{MAG}} = 0.432 \]

\[ D_{\text{MAX}} = 1 - D_{\text{MAG}} - \frac{t_r \times f_{\text{MAX}}}{2} \]

\[ \frac{N_P}{N_S} = \frac{D_{\text{MAX}} \left( V_1 - I_{\text{PP}} (R_{\text{dson}}(Q_A) + R_{CS}) \right)}{D_{\text{MAG}} (V_{\text{OUT}} + V_{DG} + V_{CBC})} \]

- \( L_{PM} \) selected based on \( f_{\text{max}} \)
  - UCC28730 requires \( D_{\text{MAG}} \) of 0.432 by design
  - Calculate \( D_{\text{MAX}} \) based on \( D_{\text{MAG}} \) and \( \frac{1}{2} \) of LC tank \( (t_r) \)
  - Use volt second balance to calculate \( \frac{N_P}{N_S} \)
Design tips and recommendations

- $R_{CS}$ and $R_{LC}$ adjusted to fine tune circuit for maximum current ($I_{OCC}$).
- Preloading ($R_{PL}$) is added/adjusted:
  - Keeps output in Reg. at no Load
    - $f_{MIN}$ is 32 Hz
    - $f_{MIN}$ is generally higher for other PSR controllers
# Device features: UCC28730

## Low Standby Power Integrated 700-V Start-up

<table>
<thead>
<tr>
<th>Features</th>
<th>Benefits</th>
</tr>
</thead>
<tbody>
<tr>
<td>▪ Less than 5mW standby power</td>
<td>▪ Exceeds energy star, coc tier 2, DOE level VI standards</td>
</tr>
<tr>
<td>▪ AM-FM modulation scheme, operates at low frequency at light loads (no burst mode)</td>
<td>▪ Maintains regulation across load range with minimal audible noise</td>
</tr>
<tr>
<td>▪ Internal 700-V startup switch with X-Cap Discharge</td>
<td>▪ Simplified fast start, lower standby power, and no leakage for bleed resistors</td>
</tr>
<tr>
<td>▪ DCM operation with FET valley switching</td>
<td>▪ Minimized switching losses to improve efficiency</td>
</tr>
<tr>
<td>▪ Frequency jitter scheme to reduce generated EMI/EMC</td>
<td>▪ Minimal external filtering to pass EMI</td>
</tr>
<tr>
<td>▪ Protection Functions: Over Voltage, Low Line &amp; Over Current</td>
<td>▪ Intelligent protection with minimal external components</td>
</tr>
</tbody>
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## Applications

- Adapters and chargers for consumer electronics
- Home appliances
- Industrial automation
- Standby and auxiliary power supplies

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![Diagram](image-url)

**VIN**

**C**

**D**

**R**

**UCC28730**

**VDD**

**HV**

**DR**

**C**

**S**

**VSC**

**GND**

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Device features: UCC24650

200V Wake-Up Monitor for Fast Transient Primary Side Regulation (PSR) Controllers

**Features**
- Less than 50μA Iq
- Fast wake-up
- No external components
- Enables secondary circuitry like synchronous rectifier
- 5-V to 28-V output monitoring

**Benefits**
- Less than 0.6mW of power consumption
- Can help to reduce output capacitances to save cost and space
- Small solution size
- No need to control across isolation barrier
- Supports a wide range of output voltages

**Applications**
- Adapters and chargers for consumer electronics
- Home appliances
- Industrial automation
- Standby and auxiliary power supplies

![Diagram of UCC24650 device](image)
Summary: UCC28730 and UCC24650

- Fast transient response ($C_{OUT}/7$)
  - High power density
  - Save $$
- Industry’s first PSR controller that help enables zero-standby ($< 5 \text{ mW}$)
- Please use design tips to simplify your design process
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