Control Challenges for Low Power AC/DC Converters

Brian King and Rich Valley
Content Outline

1. The Low Power Flyback Converter
   • Characteristics
   • Key performance
   • Typical operating and control modes

2. PSR Regulation Methods
   • Constant Voltage (CV) – regulating $V_{OUT}$
   • Constant Current (CC) – regulating $I_{OUT}$

3. Low Standby Power
   • Lowering consumption
   • Achieving low input power

4. Results and Comparison (10 W at 5 V)
   • DCM and variable frequency – primary side voltage and current control
   • DCM and fixed frequency – optical coupler feedback
   • DCM, variable frequency – optical coupler feedback, primary side current control
The Low Power AC/DC Flyback

Key Points

1. Power inductor
   - AKA, flyback transformer
   - 3rd “bootstrap” winding

2. PWM Control
   - Peak current control
   - Switching frequency control
   - Low pin count
   - Requires start-up circuit

3. Feedback
   - TL431 network
   - Optical Coupler
The Low Power AC/DC Power Supplies

3-35 Watts, 3 V to 20 V

- Universal input, 85-265 VRMS
- AC/DC adapters and chargers
- Set top boxes
- E-meters
- Auxiliary supplies – DTV, servers...

Key Parameters

- Size and cost
- Voltage and current control
- Efficiency
- Standby power
Performance – Efficiency

Efficiency standards for External Power Supplies (EPS)

- Department of Energy, DOE
- European Commission Code of Conduct, COC

![Graph showing efficiency standards for EPS]

- DOE Avg\(\eta\), July 2013
- DOE LV Avg\(\eta\), July 2013
- COC T2 Avg\(\eta\), Jan 2016
- COC T2 LV Avg\(\eta\), Jan 2016
- COC T2 10% NPP\(\eta\), Jan 2016
- COC T2 LV 10% NPP\(\eta\), Jan 2016

Nameplate Power (NPP) - Watts
Performance – Standby Power

Efficiency standards for External Power Supplies (EPS)

- European Commission, Tier 2 – January 2016: 75 mW
- Department of Energy – July 2013: 100 mW
- 5 Star Charger: 30 mW

- OEM specifications at 10 mW and asking for 5 mW
Discontinuous Current Mode (DCM)

- Single switch control
- \( T_{ON} \):
  - Switch on-time
  - Energy taken from \( V_{IN} \) and stored in primary
  - Core is “magnetized”
- \( T_{DM} \):
  - Switch is off
  - Stored energy is fully transferred to \( V_{OUT} \)
  - Core is “demagnetized”
- \( T_{DIS} \):
  - Discontinuous time
  - Currents are zero
  - \( T_{DIS} = 0 \rightarrow \) transition mode
Power Control with the DCM Flyback

- Each switching cycle
  - A controlled energy is taken from the input
  - This energy (minus some losses) is delivered to the load
  - The system is at the same condition at the beginning of every cycle

1) \[ CE_{ST} = \frac{1}{2} L_p \times I_{PRI}^{\text{peak}}^2 \] (transformer energy stored each cycle)

2) \[ P_{\text{IN}} \approx f_{\text{sw}} \times CE_{ST} \] (converter input power)

3) \[ \eta = \frac{P_{\text{OUT}}}{P_{\text{IN}}} \] (overall converter efficiency)

- Power is modulated by changing:
  - Cycles/second – frequency modulation
  - Energy/cycle – amplitude modulation
DCM or TM (Transition Mode) with Valley Switching

- Waiting for a zero crossing prevents continuous conduction mode (CCM)
- Switching on a valley reduces dissipation and EMI
- \(1/f_{SW}(\text{limit})\) sets a minimum period
DCM, Fixed Frequency Control

- Frequency is constant
- Peak current is modulated

+ Controlled switching frequency
- Lower efficiency
- High stand-by power
- Limited dynamic range

Control Law Profile
Fixed Frequency
Current Mode Control

$I_{PP}$ (Peak Primary Current)

$f_{SW}$ (set)
$I_{PP}$

Control Voltage – VCL

$f_{SW}$ (DCM)
$I_{PP}$ (DCM)

Percent of Full Output Power

$f_{SW}$ – kHz

$I_{PP}$ – % of Maximum

Fixed Frequency, 10 W at 5 V
DCM, $L_p = 750 \mu$H
DCM, Variable Frequency Control

- Peak current is modulated
- Frequency is modulated
- Approaches TM at low line full load

+ Smallest inductance
+ Good efficiency
+ Best current control
- Wide frequency range

Control Law Profile
DCM Mode

\[
\begin{align*}
I_{PP}^{(max)} & \quad I_{PP} (max) \\
I_{PP} & \quad I_{PP} (min)
\end{align*}
\]

\[
\begin{align*}
f_{SW} (max) & \quad f_{SW} (limit) \\
f_{SW} (mid) & \quad f_{SW} (min)
\end{align*}
\]

Control Voltage – VCL

- \( f_{SW} \) and \( I_{PP} \) Response with DCM Control
- \( L_P = 750 \, \mu H, 10 \, W \) at 5 V

Percent of Full Output Power

\[
\begin{align*}
f_{SW} & \quad - \quad kHz \\
I_{PP} & \quad - \quad % \text{ of Maximum}
\end{align*}
\]
TM/DCM, Variable Frequency Control

- Peak current is modulated
- Frequency is modulated
- Operates TM at full load

+ Better full load efficiency
- Larger primary inductance
- Wide frequency range
- Reduced input voltage rejection
Primary Side Regulation (PSR)

Constant Voltage (CV) and Constant Current (CC) Methods
Primary Side Regulation (PSR)

- Controlling output voltage and current with no direct sensing
- Constant Voltage (CV) for $I_O = 0$ A to $I_{OCC}$
- Constant Current (CC) for $V_O = V_{OHU}$ to $V_{OCV}$
- The output hold up voltage, $V_{OHU}$, depends on the primary controller supply dropout
PSR – Component Reduction

From This

To This

- Opto-coupler and TL431 circuits are eliminated
- Less parts = lower cost, smaller supply, higher reliability
- Less design, also less design flexibility
PSR – Feedback Concept

1. $V_{\text{OUT}} + V_D$, scaled by a turns ratio, at Aux during $T_{\text{DM}}$
2. Use for voltage feedback (at VS input)

But.....

3. Signal is not continuous
4. $N_A / N_S$ must be controlled
5. $V_D$ (output diode voltage) is a source of error
6. Nothing is this simple

Texas Instruments – 2014/15 Power Supply Design Seminar
PSR – Feedback Concept

Auxiliary winding waveform:

Leakage inductance
- Reset spike
- Rings with $C_{SWN}$

1. ESR
   - $I_{SEC} \times R_{ESR}$ slope

2. $C_{SWN}$ rings with $L_P$

Best regulation if sampled when $I_{SEC}$ goes to zero

$\rightarrow$ “VS sample”
PSR – Voltage Loop

- Samples output at $f_{SW}$ rate
- $f_{SW}$ has wide range, >100:1, for low stand-by power
- Compensation ($M(s)$) done internally

$$\frac{(V_{OUT} + V_D) \times N_A}{N_S}$$

Controller

Sampler

$A_{EA}$

$M(s)$

Control Law

Minimum Period and Peak Primary Current

GD

DRV

CS

VCL, filtered E/A output and input to the Control Law function

$R_{CS}$

$R_{LOAD}$

$V_{BULK}$

$V_{OUT}$

$V_{D}$

ESR impact ~ 0 since $V_{OUT}$ is sampled with the secondary loop current = 0
Poor Transient Response from Zero Load

1. Low switching frequencies

2. Feedback is only available during a switching event

3. Poor transient performance, or a very large output capacitor

As Bad as:

\[
\Delta V_{OUT} = \frac{I_{OUT}(\text{step})}{C_{OUT} \times f_{SW}(\text{min})}
\]
PSR Voltage Error Sources

• Reference, Error Amplifier, Resistors

• Rectifier Diode Drop
  – Actually regulating $V_{OUT} + V_D$
  – Diode-to-diode $V_D$ at a fixed low current is consistent for a given diode selection
  – Diode temperature variation will impact $V_{OUT}$ if not compensated for

• Transformer
  – Reasonable manufacturing gives good turn control
  – Impact of leakage inductance is small

• Winding Voltage Sampling Errors (generally seen at light loads)
  – Auxiliary diode, snubber diode, snubber noise corrupting signal
  – Auxiliary to secondary cross-regulation at light loads
  – VS filtering

• Generally +/- 5% is readily achievable across line and load
Constant Current Control – Concept

1) \( I_O = I_{SEC}(Avg) = \frac{I_{SEC}(peak)}{2} \times \frac{T_{DM}}{T_{SW}} \)

2) \( I_{SEC}(peak) = I_{PRI}(peak) \times \frac{N_P}{N_S} \)

Therefore: 3) \( I_O = \frac{I_{PRI}(peak)}{2} \times \frac{N_P}{N_S} \times \frac{T_{DM}}{T_{SW}} \)

- Controlling the peak primary current and the demagnetization duty-cycle \( (T_{DM} / T_{SW}) \) will regulate the output current accurately (~+/-5% achievable)
Standby Power ($P_{SB}$)

Power consumed with zero external load, a very common state for power supplies.
**P_{SB} Components**

\[ P_{SB} = f_{SW}(sb) \times CE_{IN}(\text{min}) + P_{STRT} + P_{LKG} \]

Where:

- \( f_{SW}(sb) \) = converter switching frequency during stand-by
- \( CE_{IN}(\text{min}) \) = converter minimum input cycle energy
- \( P_{STRT} \) = Start-up power
- \( P_{LKG} = \sum \) Capacitor and junction leakage losses

- Generally \( f_{SW} \times CE_{IN} \) dominates
  - Encompasses output preload and primary bias power
- \( P_{STRT} \) can be significant at low target \( P_{SB} \)
**P_{SB} – Start-Up**

**Resistive Start-Up:**
7-300 mW to P_{SB}

**Active Start-Up:**
No P_{SB} penalty

\[ V_{AUX} \text{ level during } T_{DM} = (V_O + V_D) \frac{N_A}{N_S} \]

\[ V_{VDD} \]
\textbf{P}_{SB} \textit{Control Law Must Haves}

- Low input energy / cycle
- Low switching frequency
- Constant time / cycle
  - Burst mode versus constant \( f_{SW}(sb) \)
  - Same average cycles / second – worse transient response
**P_{SB} and CE_{IN}(min)**

- The minimum cycle energy is dependent on the AM range and $f_{SW}(\text{max})$

\[
\text{CE}_{\text{IN}}(\text{min}) = \frac{P_O(\text{max})}{\eta_T \times f_{SW}(\text{@ P max})} \left( \frac{1}{K_{AM}} \right)^2
\]

where: 
\[
K_{AM} = \frac{I_{PRI(\text{peak, @ P max})}}{I_{PRI(\text{peak, min})}}
\]

- The maximum AM range, $K_{AM}$, will typically be limited to 3-5
- This expression does not take into account the impact of the switch-node capacitance
- $\eta_T$ is an efficiency estimate ignoring capacitive and bias loss
\( P_{SB} \) – Switch Node Capacitance Impact

- Delta input cycle energy

\[
\Delta CE_{IN} (\text{cap, total}) = C_{SWN} \times V_{BLK}^2
\]

- A portion of this is dissipated in the switch and tank,

\[
\Delta CE_{IN} (\text{cap, dissipated}) = \frac{1}{2} \times C_{SWN} \times \left( V_{BLK}^2 + V_R^2 \right)
\]

- A portion goes into the transformer \( \rightarrow \) output,

\[
\Delta CE_{IN} (\text{cap, out}) = \frac{1}{2} \times C_{SWN} \times \left( V_{BLK}^2 - V_R^2 \right)
\]
P_{SB} – Switch Node Capacitance Impact

For the example to the right ignoring the effect of $C_{SWN}$:

$CE_{IN} (\text{min}) = 7.81 \mu J$

$CE_{OUT} (\text{min}) = \eta_T \times CE_{IN} (\text{min}) = 6.25 \mu J$

Incremental energy due to $C_{SWN}$:

$\Delta CE_{IN} (\text{cap, total}) = 9.33 \mu J$

$\Delta CE_{IN} (\text{cap, dissipated}) = 4.89 \mu J$

$\Delta CE_{IN} (\text{cap, out}) = 4.44 \mu J$

$\Delta CE_{OUT} (\text{cap, out}) = \eta_T \times \Delta CE_{IN} (\text{cap, out}) = 3.55 \mu J$

Total minimum energy w/ $C_{SWN}$:

$CE_{IN} (\text{min, total}) = 7.81 \mu J + 9.33 \mu J = 17.14 \mu J$

$CE_{OUT} (\text{min, total}) = 6.25 \mu J + 3.55 \mu J = 9.80 \mu J$

Example Power Supply Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$P_O (\text{max})$</td>
<td>10 W</td>
</tr>
<tr>
<td>$f_{SW} (\text{max})$</td>
<td>100 kHz</td>
</tr>
<tr>
<td>$V_{BLK} (\text{max})$</td>
<td>365 V</td>
</tr>
<tr>
<td>$V_R (\text{nom})$</td>
<td>80 V</td>
</tr>
<tr>
<td>$K_{AM}$</td>
<td>4</td>
</tr>
<tr>
<td>$C_{SWN}$</td>
<td>70 pF</td>
</tr>
<tr>
<td>$\eta_T^*$</td>
<td>80%</td>
</tr>
</tbody>
</table>

$\eta_T^*$ Efficiency estimate ignoring capacitive and bias loss

Limits very light load efficiency and dictates a minimum load
**P_{SB} – Minimum Load Requirements**

- The converter has a minimum load it will deliver that is equal to:

\[
P_{o}(s_{b, total}) > f_{SW} (\text{min}) \times \left( \frac{P_{O} (@ P_{max})}{f_{SW} (@ P_{max})} \left( \frac{1}{K_{AM}} \right)^2 + \frac{\eta_{T} \times C_{SWN} \times (V_{BLK}^2 - V_{R}^2)}{2} \right)
\]

- Bias power plus a preload will adjust \(f_{SW(s_b)}\) to approach \(f_{SW(\text{min})}\), or exceed for improved transient response

- If the preload is not adequate then regulation will be lost with \(V_{O}\) rising
$P_{SB} – Versus Transient Response$

\[ P_{IN}(sb, \text{total}) > f_{SW}(sb) \times \left( \frac{P_O(\text{max})}{\eta_T \times f_{SW}(\text{@Pmax})} \left( \frac{1}{K_{AM}} \right)^2 + C_{SWN} \times 2 \text{ VAC}_{RMS}^2 \right) \]

\[ P_{OUT}(sb) \text{ and Transient Delta Versus } f_{SW}(sb) \]

5 V, 10 W Example
$C_{OUT} = 820 \ \mu\text{F}$
VAC = 260

For: $\Delta V_O < 10%$
\[ \rightarrow f_{SW} > 1200 \ \text{Hz} \]
\[ \rightarrow 12 \ \text{mW} \ P_{OUT} \]

\[ P_{IN}(sb) \text{ and } f_{SW}(sb) \text{ Versus VAC} \]

5 V, 10 W Example
Adjusting $P_{OUT}(sb) = 12 \ \text{mW}$
$f_{SW}(sb) > 1 \ \text{kHz}$

$C_{SWN} \text{ Impact on } f_{SW} \text{ and PSB}$
Low Power Flyback Control Recap

• Discontinuous operation with variable frequency optimizes efficiency across load

• Primary side regulation can provide good V and I regulation but transient response can suffer

• Standby power benefits from:
  – Low switching frequencies
  – Low bias and start-up overhead
  – Low switch-node capacitance
Results and Comparison

How do different controllers affect the performance of a typical power supply?
AC/DC 5 V / 10 W Adaptor

General Specifications:
- Universal AC input: 85 V to 265 V, 50/60 Hz
- 5 V output; 2 A max output current

Control Methodologies Evaluated:
- DCM, fixed-frequency, control with opto feedback (DCM/FF/Opto)
- DCM with valley switching and PSR (DCM/VS/PSR)
- DCM with valley switching and opto feedback (DCM/VS/Opto)

Controlled Parameters:
- All designs operate at ~100 kHz at maximum load
- Same transformer, FET, diode used on all designs
DCM/FF/Opto Example

1. Start-up resistors increase standby power
2. Large bias cap; factors include $I_{DD}$, opto current, UVLO hysteresis
3. TL431 and opto-coupler for regulation
4. Faster loop response allows smaller output caps
5. Minimum on-time requires turn-on resistor at no load operation
DCM/VS/PSR Example

1. No start-up resistors (lower standby)
2. Small bias capacitor
3. PSR eliminates opto-coupler and TL431
4. Larger output capacitors needed for transients
5. Small pre-load resistor needed for no load operation
1. No start-up resistors (lower standby power)
2. Medium sized bias capacitor
3. TL431 and opto-coupler regulation
4. Faster loop response allows smaller output caps
Photographs

DCM/FF/ Opto
www.ti.com/tool/pmp9203

DCM/VS/PSR
www.ti.com/tool/pmp9202

DCM/VS/ Opto
www.ti.com/tool/pmp9204

1. Start-up resistors
2. Bias capacitor
3. TL431 and opto-coupler
4. Bias capacitor
Load Regulation

- TL431 and opto-coupler provides excellent load regulation
- PSR uses cable-drop compensation
  - Compensates for resistive drops on the secondary side
  - Keeps load regulation within +/-1%
Overload Protection

- Traditional fixed-frequency controller:
  - Frequency and peak current held constant
  - Currents during overload can become excessive
- DCM/VS controllers include current regulation feature
Efficiency

- All designs achieve >80% efficiency at max load
- DCM/VS controllers provide better efficiency at low to medium loads
  - Due to reduced frequency operation
- Start-up resistors have major impact at higher input voltages
Standby Power Consumption

- Pre-load resistor of PSR design accounts for a large portion of $P_{sb}$
- TL431 and opto-coupler biasing increases $P_{sb}$
- Fixed frequency example $P_{sb}$ dominated by start-up resistors
Load Transient Response

- PSR response varies
  - Dependent on when in the switching cycle the transient hits
  - Starting at 0 A vs. a few mA makes a big difference

- TL431 and opto-coupler response is predictable
  - Dependent on output capacitance and bandwidth
Small Form Factor Example

- DCM/VS/PSR example design can be laid out to fit into a 1”x1” cube
- Two secondary transformer wires are the only electrical connection between the two circuit boards (not possible with opto feedback)
- Small product size requires efficiency >80% to prevent thermal issues
- PMP8363 available on PowerLab: http://www.ti.com/tool/pmp8363
# Comparison Summary

<table>
<thead>
<tr>
<th></th>
<th>DCM/FF/Opto</th>
<th>DCM/VS/PSR</th>
<th>DCM/VS/Opto</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Output Voltage Accuracy</strong></td>
<td>+/-2%</td>
<td>+/-5%</td>
<td>+/-2%</td>
</tr>
<tr>
<td><strong>Load Regulation</strong></td>
<td>+/-0.1%</td>
<td>+/-0.6%</td>
<td>+/-0.1%</td>
</tr>
<tr>
<td><strong>Max Load Eff.</strong></td>
<td>82.0% / 80.4%</td>
<td>82.2% / 82.5%</td>
<td>81.3% / 81.7%</td>
</tr>
<tr>
<td>(115 VAC / 230 VAC)</td>
<td>82.0% / 80.4%</td>
<td>82.2% / 82.5%</td>
<td>81.3% / 81.7%</td>
</tr>
<tr>
<td><strong>Standby Power</strong></td>
<td>216 mW / 584 mW</td>
<td>14 mW / 16 mW</td>
<td>57 mW / 64 mW</td>
</tr>
<tr>
<td>(115 VAC / 230 VAC)</td>
<td>216 mW / 584 mW</td>
<td>14 mW / 16 mW</td>
<td>57 mW / 64 mW</td>
</tr>
<tr>
<td><strong>Load Transients</strong></td>
<td>-200 mV</td>
<td>-1100 mV</td>
<td>-200 mV</td>
</tr>
<tr>
<td>(0 A to 2 A)</td>
<td>-200 mV</td>
<td>-1100 mV</td>
<td>-200 mV</td>
</tr>
<tr>
<td><strong>Current Regulation</strong></td>
<td>Not Provided</td>
<td>+/-5%</td>
<td>+/-5%</td>
</tr>
<tr>
<td><strong># of Components</strong></td>
<td>41</td>
<td>27</td>
<td>37</td>
</tr>
<tr>
<td><strong>Relative Cost</strong></td>
<td>Low</td>
<td>Lowest</td>
<td>Low</td>
</tr>
</tbody>
</table>
Texas Instruments Incorporated and its subsidiaries (TI) reserve the right to make corrections, enhancements, improvements and other changes to its semiconductor products and services per JESD46, latest issue, and to discontinue any product or service per JESD48, latest issue. Buyers should obtain the latest relevant information before placing orders and should verify that such information is current and complete. All semiconductor products (also referred to herein as “components”) are sold subject to TI’s terms and conditions of sale supplied at the time of order acknowledgment.

TI warrants performance of its components to the specifications applicable at the time of sale, in accordance with the warranty in TI’s terms and conditions of sale of semiconductor products. Testing and other quality control techniques are used to the extent TI deems necessary to support this warranty. Except where mandated by applicable law, testing of all parameters of each component is not necessarily performed.

TI assumes no liability for applications assistance or the design of Buyers’ products. Buyers are responsible for their products and applications using TI components. To minimize the risks associated with Buyers’ products and applications, Buyers should provide adequate design and operating safeguards.

TI does not warrant or represent that any license, either express or implied, is granted under any patent right, copyright, mask work right, or other intellectual property right relating to any combination, machine, or process in which TI components or services are used. Information published by TI regarding third-party products or services does not constitute a license to use such products or services or a warranty or endorsement thereof. Use of such information may require a license from a third party under the patents or other intellectual property of the third party, or a license from TI under the patents or other intellectual property of TI.

Reproduction of significant portions of TI information in TI data books or data sheets is permissible only if reproduction is without alteration and is accompanied by all associated warranties, conditions, limitations, and notices. TI is not responsible or liable for such altered documentation. Information of third parties may be subject to additional restrictions.

Resale of TI components or services with statements different from or beyond the parameters stated by TI for that component or service voids all express and any implied warranties for the associated TI component or service and is an unfair and deceptive business practice. TI is not responsible or liable for any such statements.

Buyer acknowledges and agrees that it is solely responsible for compliance with all legal, regulatory and safety-related requirements concerning its products, and any use of TI components in its applications, notwithstanding any applications-related information or support that may be provided by TI. Buyer represents and agrees that it has all the necessary expertise to create and implement safeguards which anticipate dangerous consequences of failures, monitor failures and their consequences, lessen the likelihood of failures that might cause harm and take appropriate remedial actions. Buyer will fully indemnify TI and its representatives against any damages arising out of the use of any TI components in safety-critical applications.

In some cases, TI components may be promoted specifically to facilitate safety-related applications. With such components, TI’s goal is to help enable customers to design and create their own end-product solutions that meet applicable functional safety standards and requirements. Nonetheless, such components are subject to these terms.

No TI components are authorized for use in FDA Class III (or similar life-critical medical equipment) unless authorized officers of the parties have executed a special agreement specifically governing such use.

Only those TI components which TI has specifically designated as military grade or “enhanced plastic” are designed and intended for use in military/aerospace applications or environments. Buyer acknowledges and agrees that any military or aerospace use of TI components which have not been so designated is solely at the Buyer’s risk, and that Buyer is solely responsible for compliance with all legal and regulatory requirements in connection with such use.

TI has specifically designated certain components as meeting ISO/TS16949 requirements, mainly for automotive use. In any case of use of non-designated products, TI will not be responsible for any failure to meet ISO/TS16949.