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

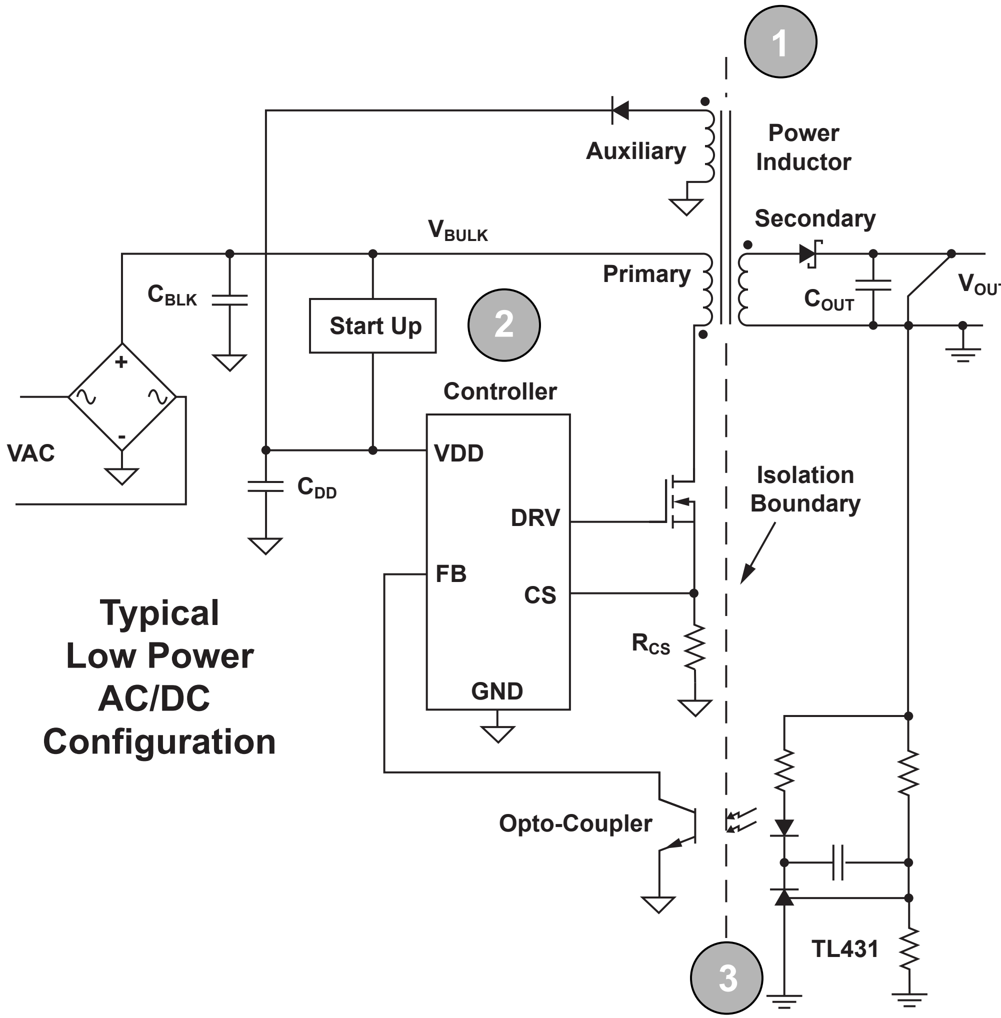
The Low Power AC/DC Flyback

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

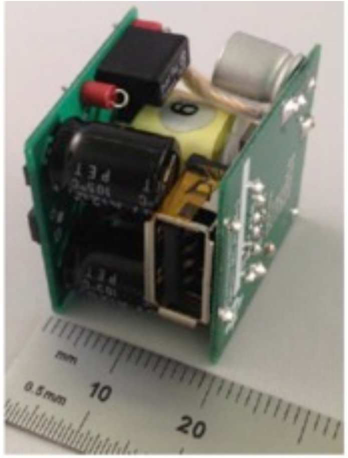


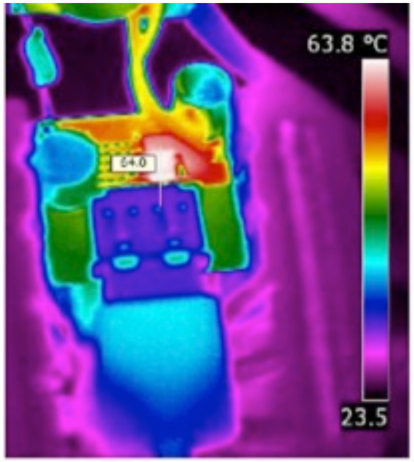
Typical Low Power AC/DC Configuration

The Low Power AC/DC Power Supplies

3-35 Watts, 3 V to 20 V

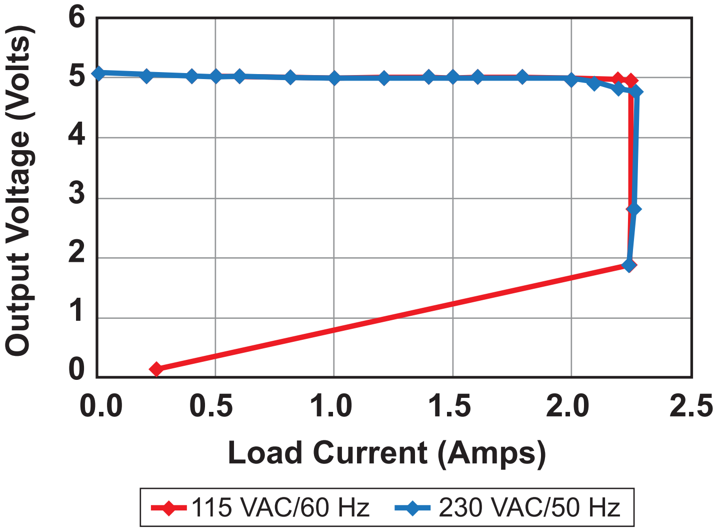
- Universal input, 85-265 VRMS
- AC/DC adapters and chargers
- Set top boxes
- E-meters
- Auxiliary supplies – DTV, servers…





Key Parameters

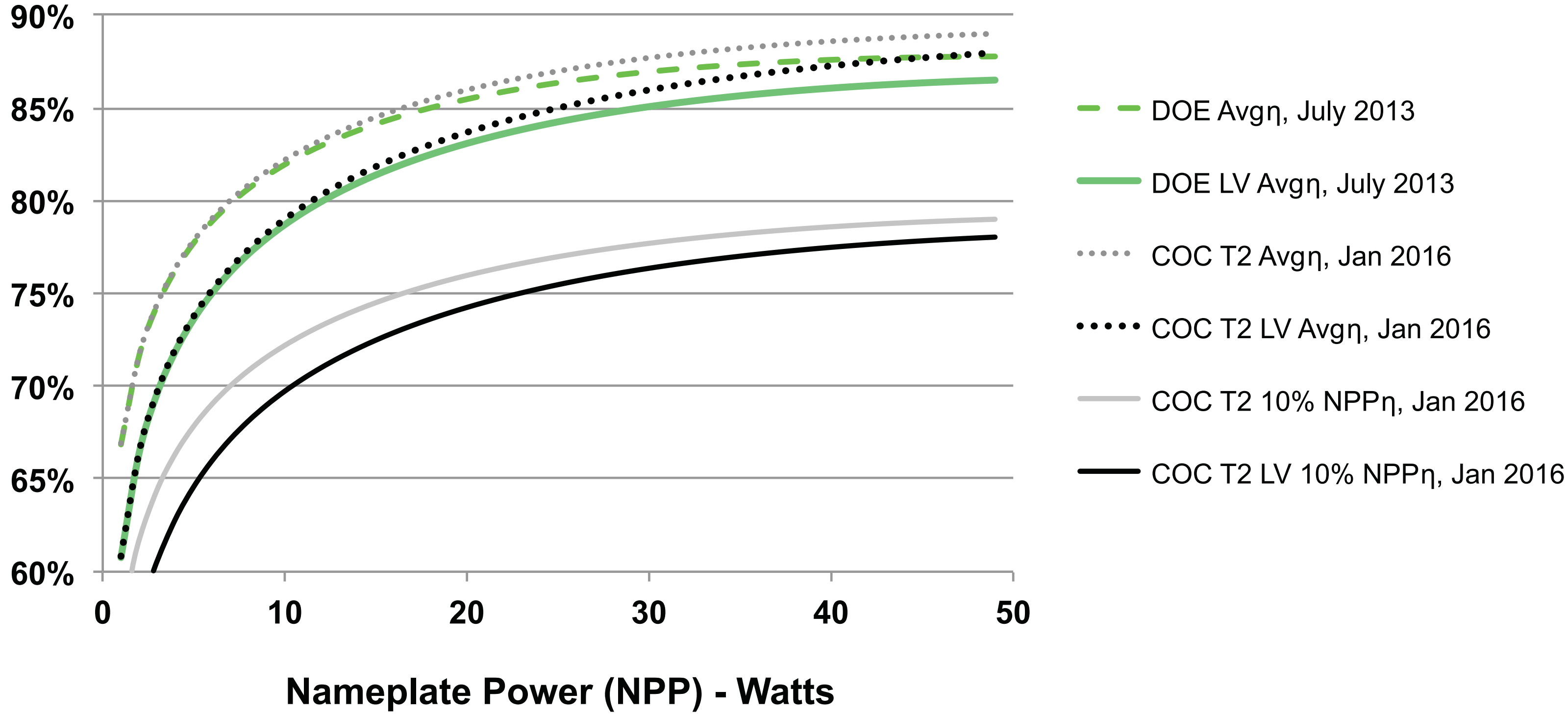
- Size and cost
- Voltage and current control
- Efficiency
- Standby power



Performance – Efficiency

Efficiency standards for External Power Supplies (EPS)

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



Performance – Standby Power

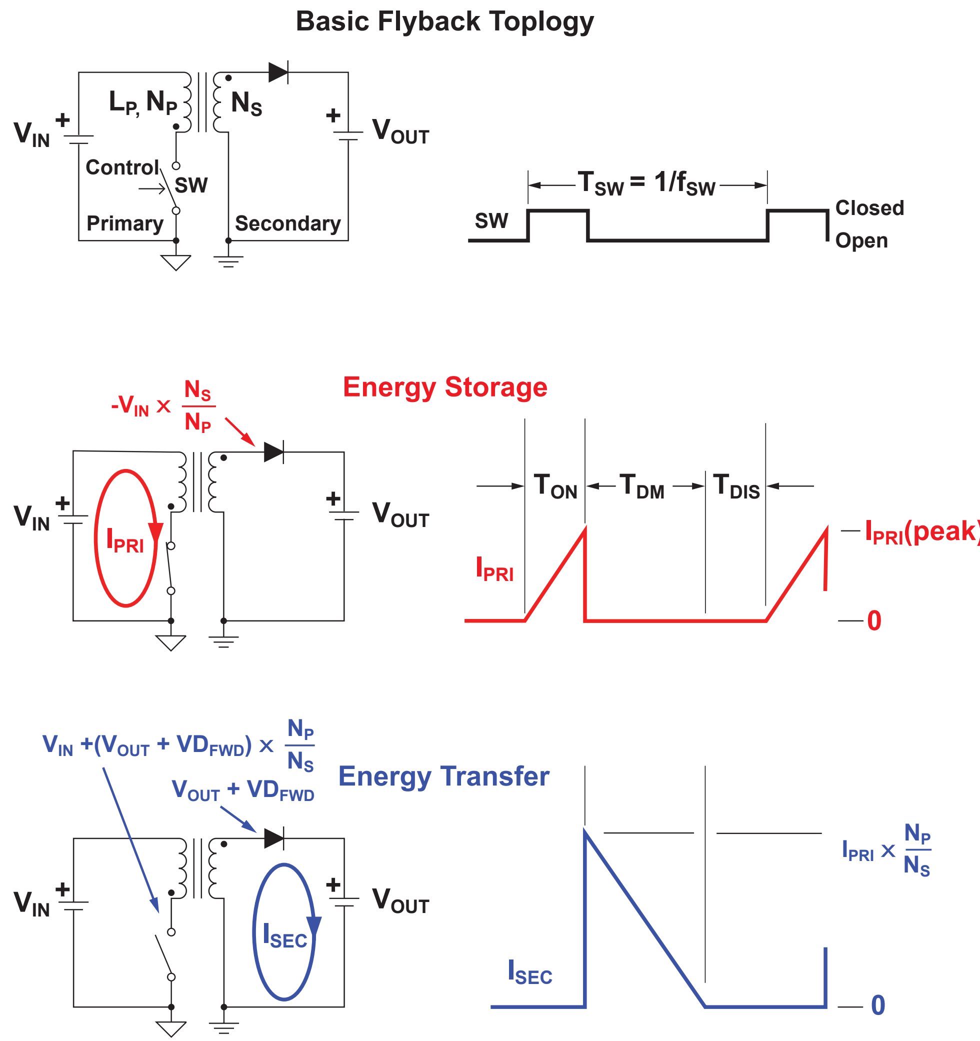
Efficiency standards for External Power Supplies (EPS)

- 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

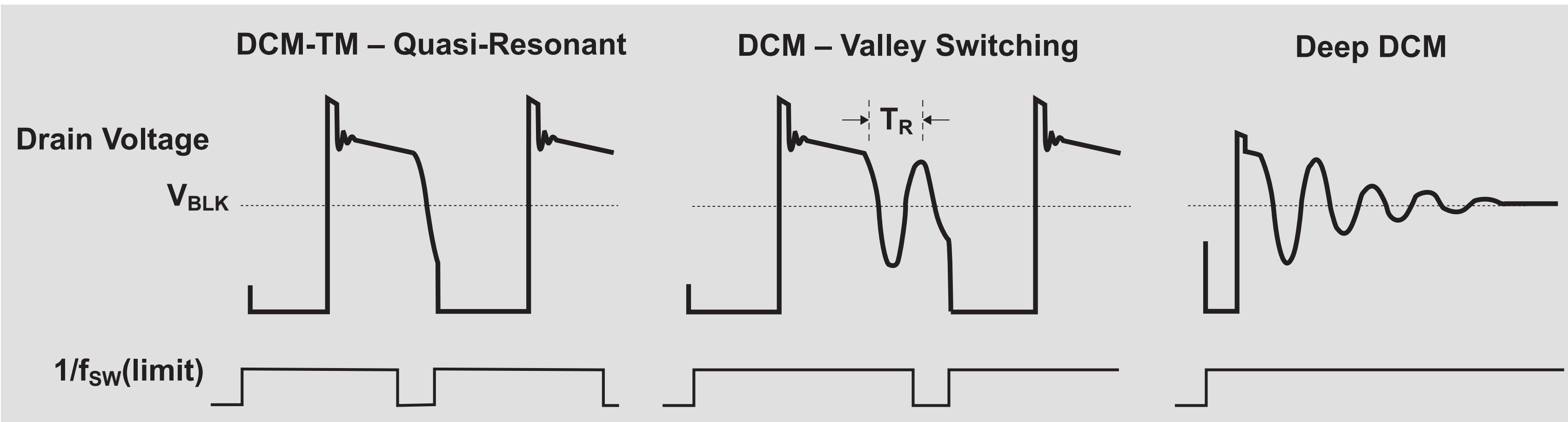
1) $CE_{ST} = \frac{1}{2} L_P \times I_{PRI}(\text{peak})^2$ (transformer energy stored each cycle)

2) $P_{IN} \cong fsw \times CE_{ST}$ (converter input power)

3) $\eta = \frac{P_{OUT}}{P_{IN}}$ (overall converter efficiency)

- Power is modulated by changing:
  - Cycles/second – frequency modulation
  - Energy/cycle – amplitude modulation

DCM or TM(Transition Mode) with Valley Switching

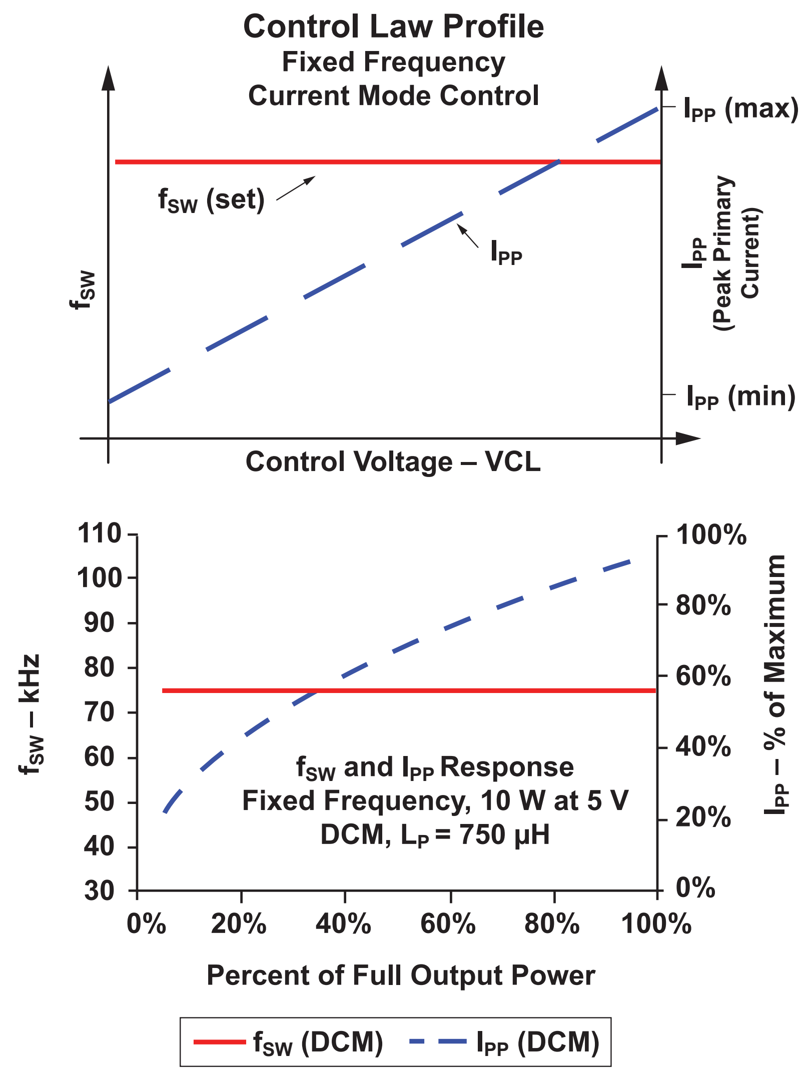


- Waiting for a zero crossing prevents continuous conduction mode (CCM)
- Switching on a valley reduces dissipation and EMI
- $1/f_{SW}$(limit) sets a minimum period

DCM, Fixed Frequency Control

- Frequency is constant
- Peak current is modulated

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



DCM, Variable Frequency Control

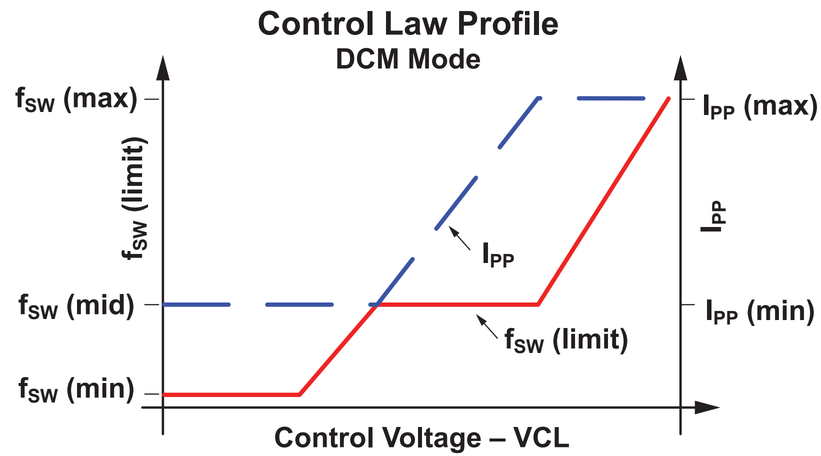
- Peak current is modulated
- Frequency is modulated
- Approaches TM at low line full load

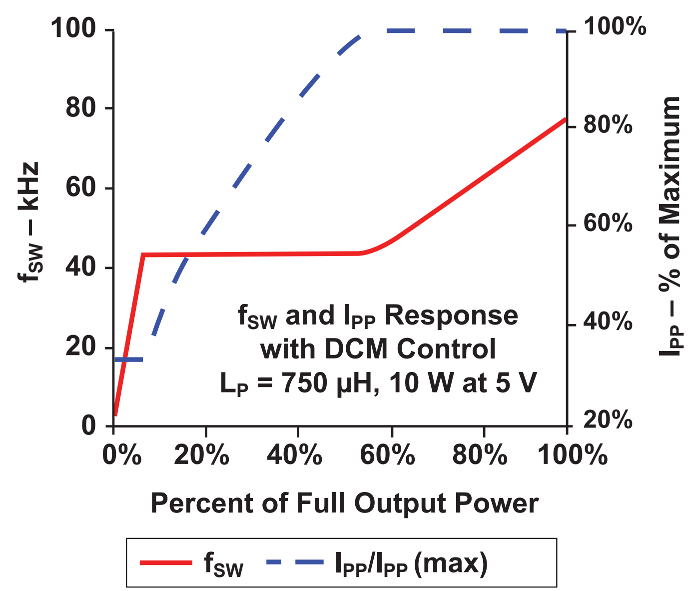
\+ Smallest inductance

\+ Good efficiency

\+ Best current control

– Wide frequency range

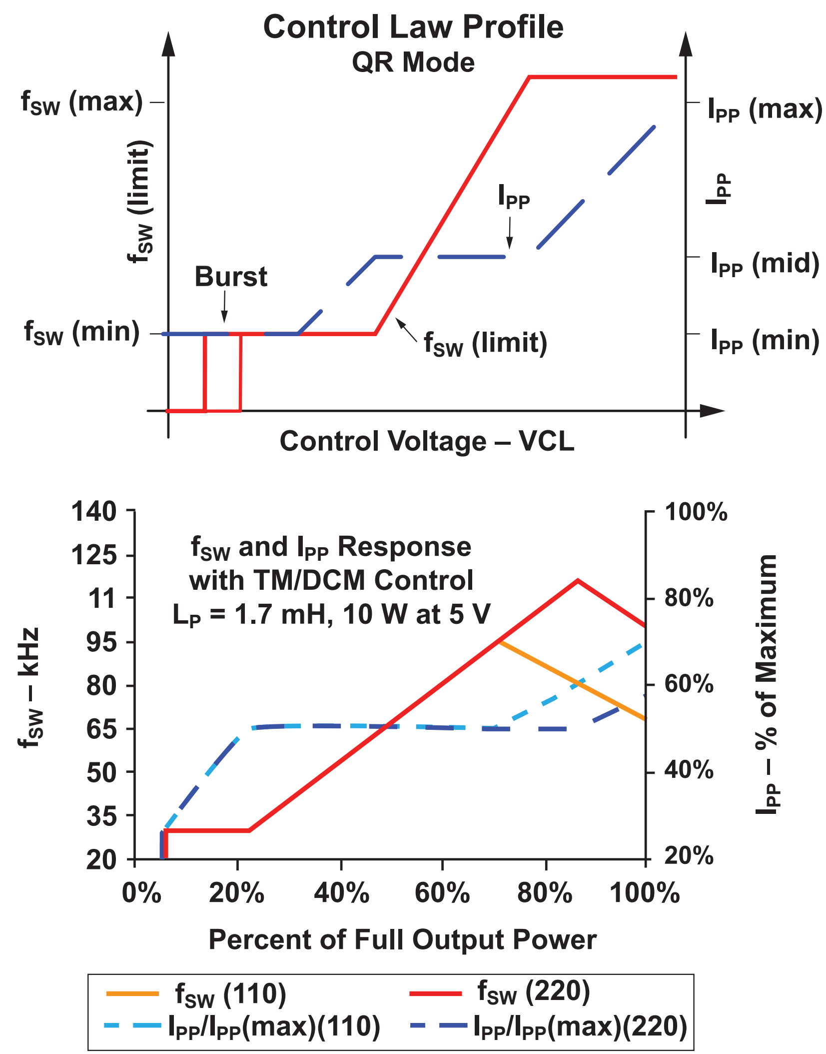




TM/DCM, Variable Frequency Control

- 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

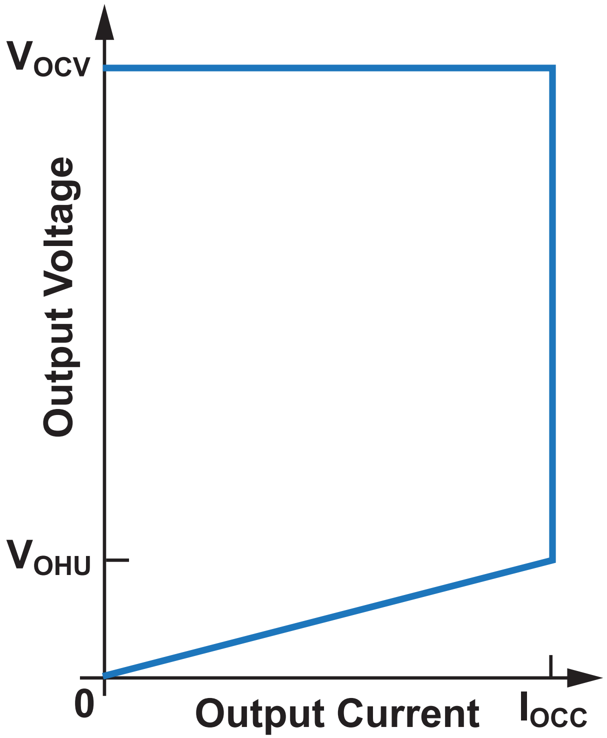


Primary Side Regulation (PSR)

Constant Voltage (CV) and
Constant Current (CC) Methods

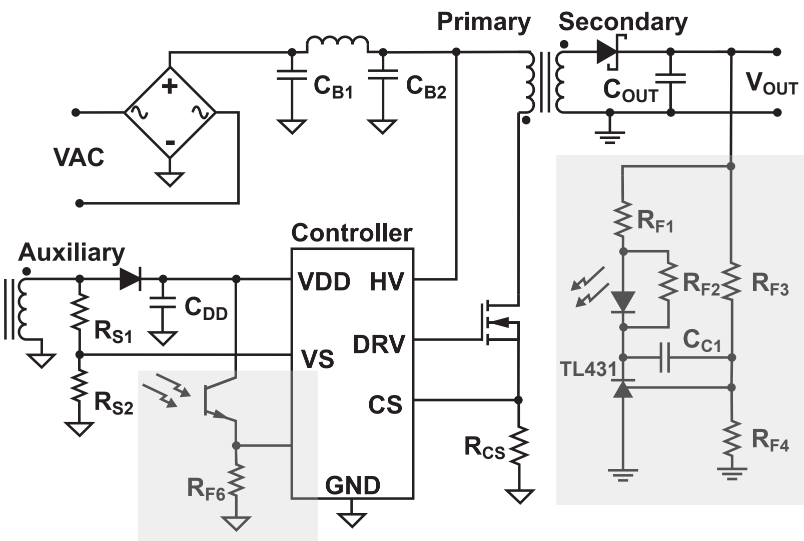
Primary Side Regulation (PSR)

- 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



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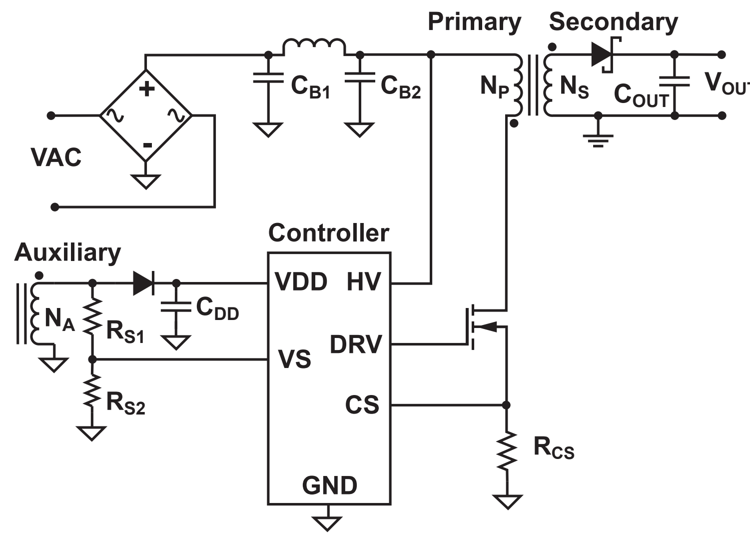


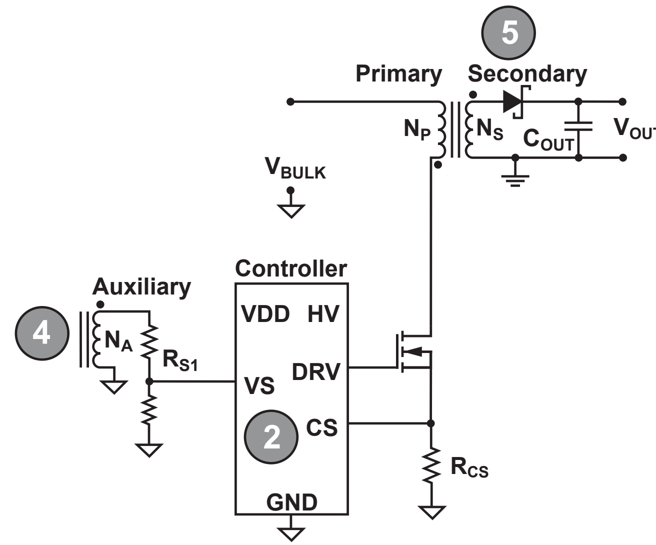
- Opto-coupler and TL431 circuits are eliminated
- Less parts = lower cost, smaller supply, higher reliability
- Less design, also less design flexibility

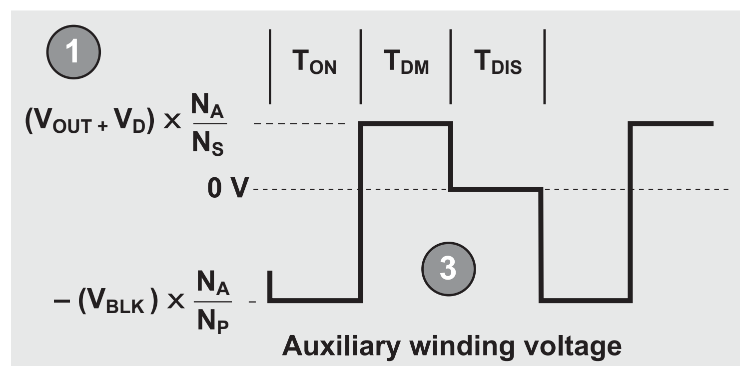
PSR – Feedback Concept

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

But…..

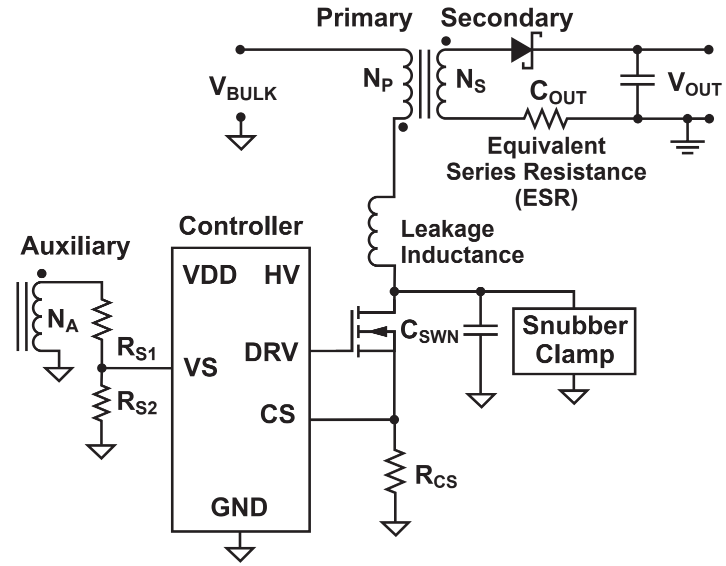
3. Signal is not continuous
4. N_A / N_S must be controlled
5. V_D (output diode voltage) is a source of error
6. Nothing is this simple





T_{ON} = the switch ON time
T_{DM} = the transformer demagnetization time
T_{DIS} = the discontinuous current time

PSR – Feedback Concept



Auxiliary winding waveform:

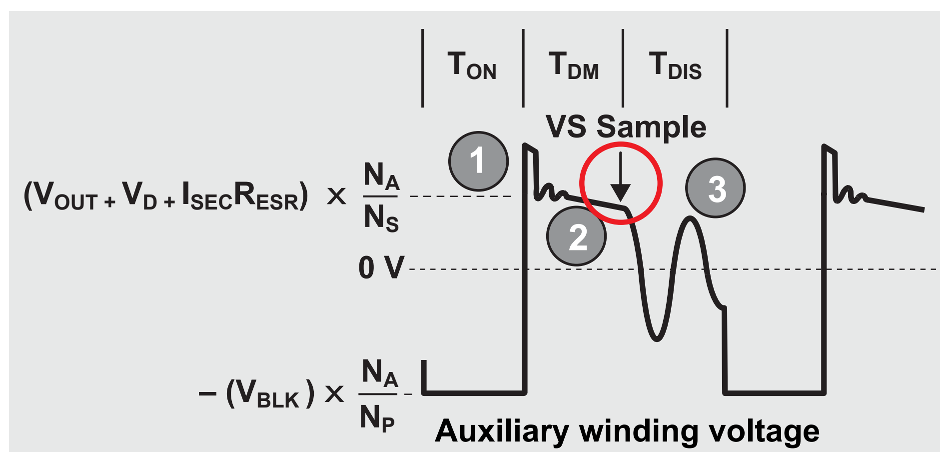
Leakage inductance

- Reset spike
- Rings with C_{SWN}

1. ESR
   - $I_{SEC} \times R_{ESR}$ slope
2. C_{SWN} rings with L_P

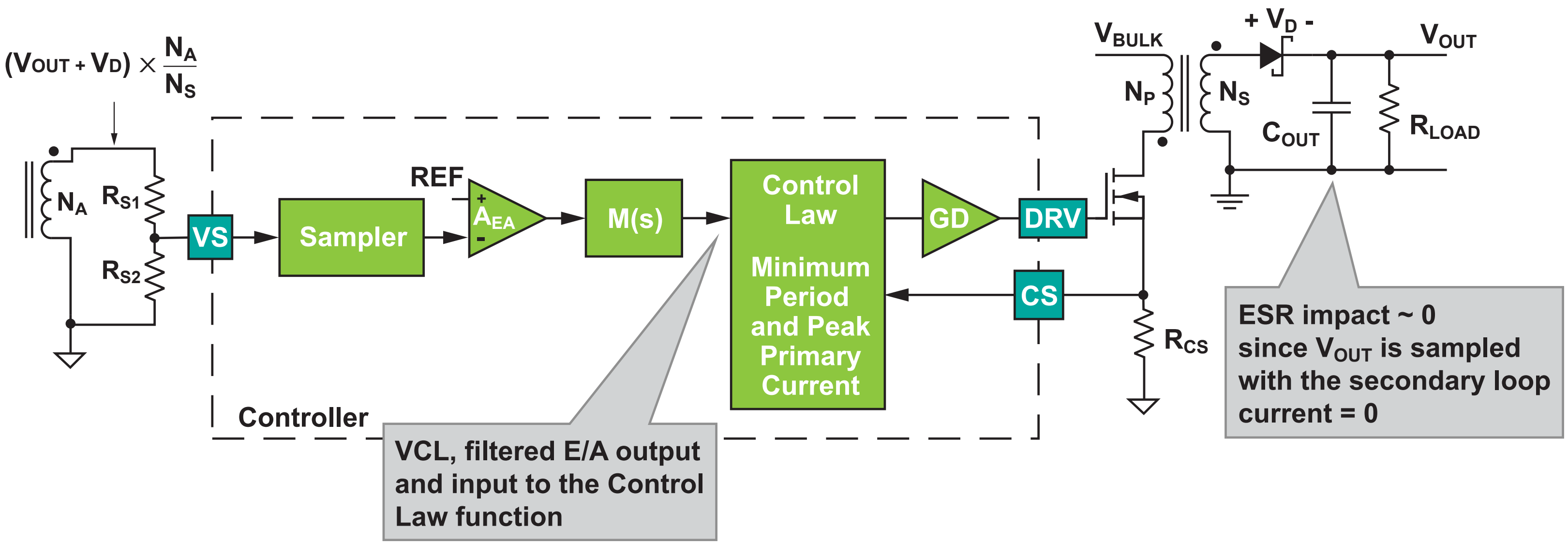
Best regulation if sampled when I_{SEC} goes to zero

→ "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



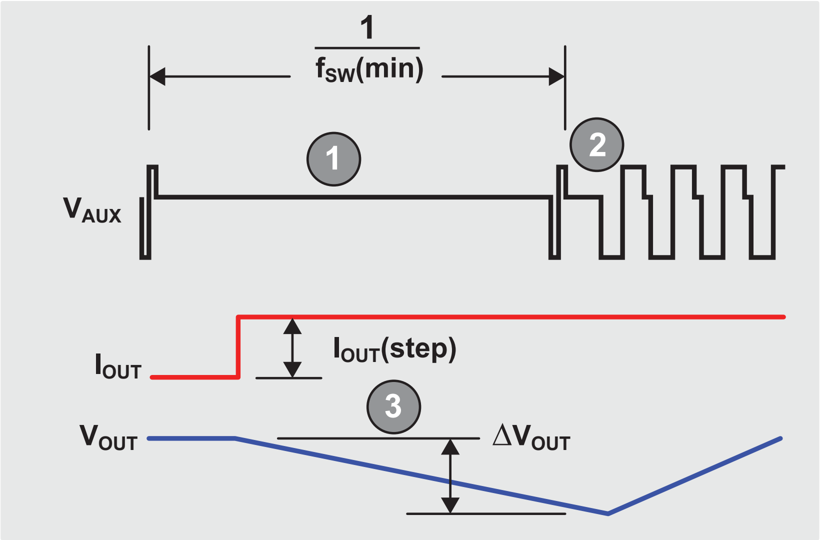
PSR – Transient Response Problem

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:

$$\Delta V_{OUT} = \frac{I_{OUT}(step)}{C_{OUT} \times f_{SW}(min)}$$

PSR Voltage Error Sources

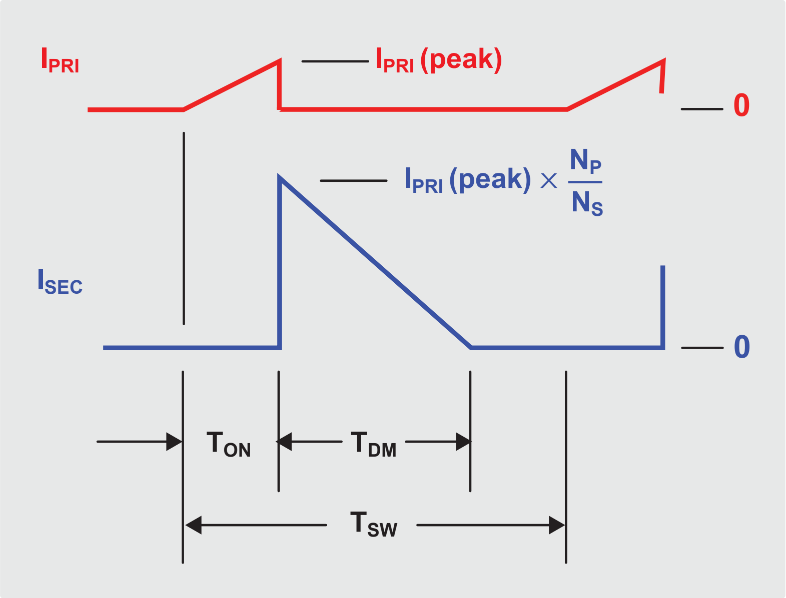
- Reference, Error Amplifier, Resistors
- Rectifier Diode Drop
  - Actually regulating V_{OUT} + V_D
  - Diode-to-diode V_D at a fixed low current is consistent for a given diode selection
  - Diode temperature variation will impact V_{OUT} if not compensated for
- Transformer
  - Reasonable manufacturing 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

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

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

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



- 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

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

Where:

$f_{SW}(sb) =$ converter switching frequency during stand-by

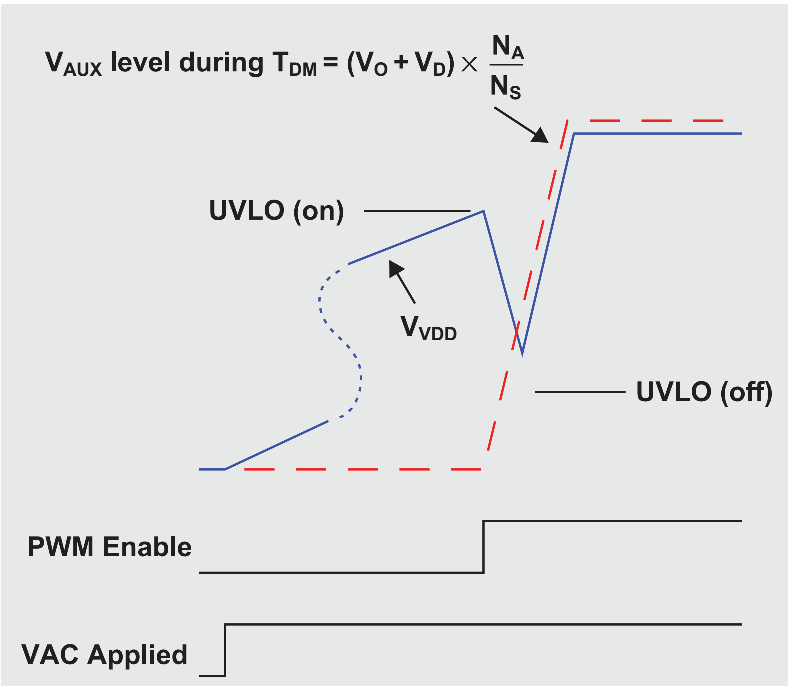
$CE_{IN}(min) =$ converter minimum input cycle energy

$P_{STRT} =$ Start-up power

$P_{LKG} = \sum$ Capacitor and junction leakage losses

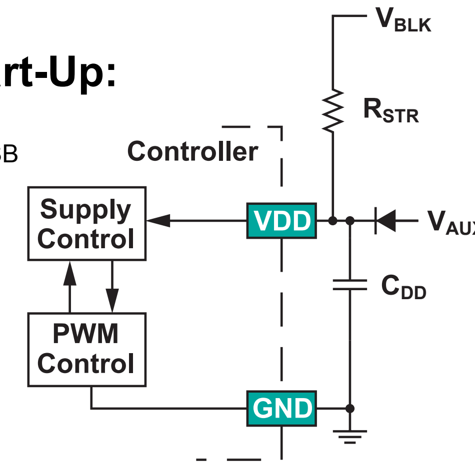
- Generally f_{SW} x CE_{IN} dominates
  - Encompasses output preload and primary bias power
- P_{STRT} can be significant at low target P_{SB}

P_{SB} – Start-Up



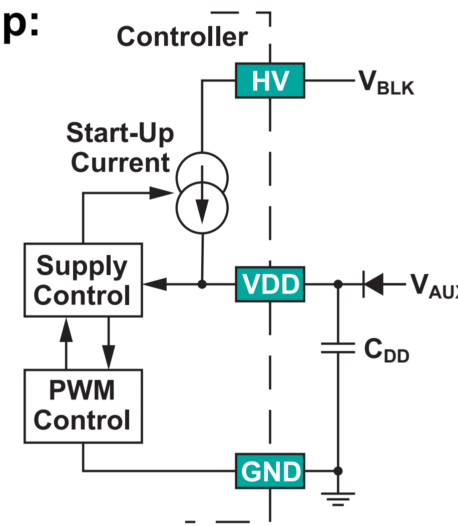
Resistive Start-Up:

7-300 mW to P_{SB}

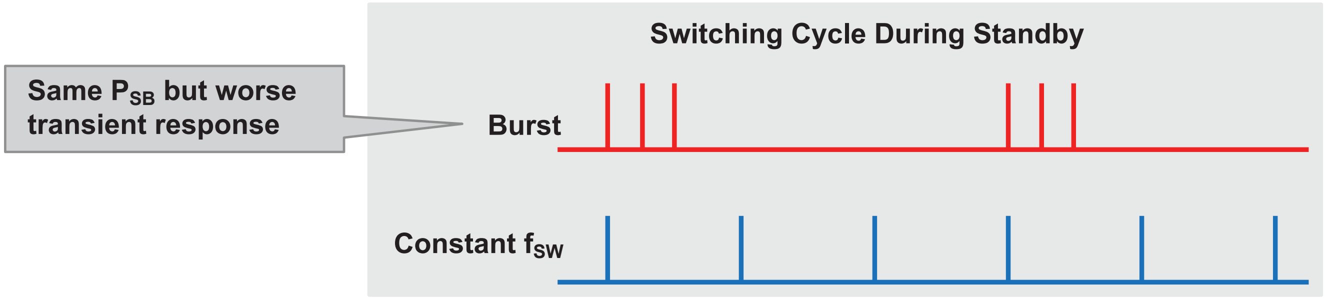


Active Start-Up:

No P_{SB} penalty



P_{SB} 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

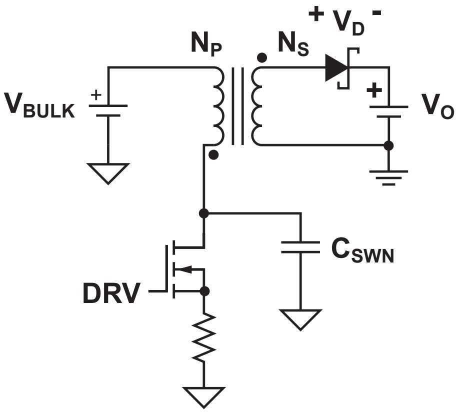
P_{SB} and CE_{IN}(min)

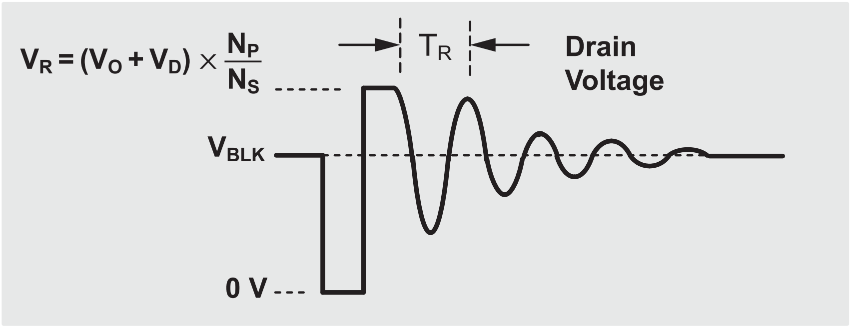
- The minimum cycle energy is dependent on the AM range and f_{SW}(max)

$$CE_{IN}(min) = \frac{P_O(max)}{\eta_T \times f_{SW}(@P\,max)} \left(\frac{1}{K_{AM}} \right)^2 \qquad \text{where: } K_{AM} = \frac{I_{PRI}(peak, @P\,max)}{I_{PRI}(peak, min)}$$

- 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
- η_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 → 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}:

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

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

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

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

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	
P_O (max)	10 W
f_{SW} (max)	100 kHz
V_{BLK} (max)	365 V
V_R (nom)	80 V
K_{AM}	4
C_{SWN}	70 pF
η_T*	80%

* Efficiency estimate ignoring capacitive and bias loss

Limits very light load efficiency and dictates a minimum load

P_{SB} – Minimum Load Requirements

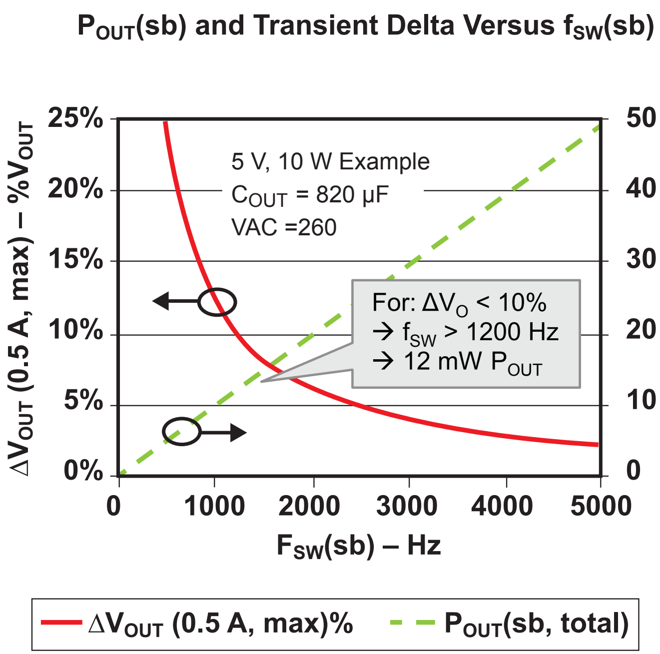
- The converter has a minimum load it will deliver that is equal to:

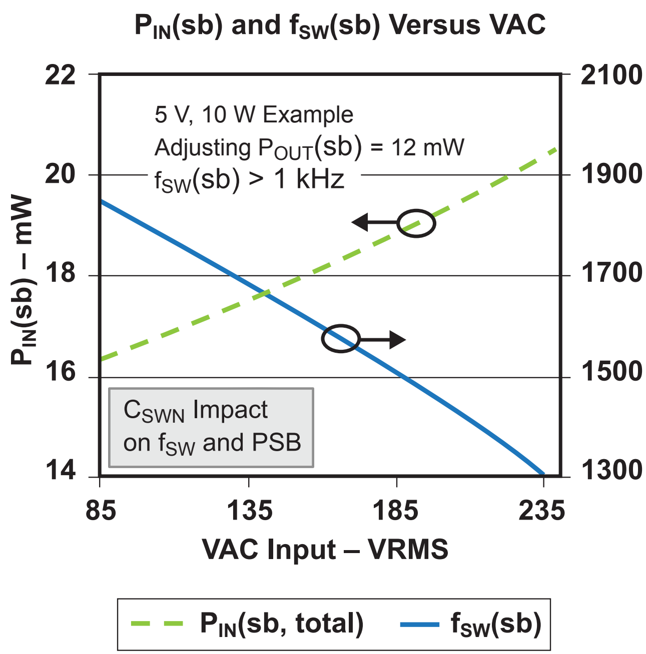
$$P_O(sb,\ total) > f_{SW}(min) \times \left(\frac{P_O(@P\max)}{f_{SW}(@P\max)} \left(\frac{1}{K_{AM}} \right)^2 + \frac{\eta_T \times C_{SWN} \times (V_{BLK}{}^2 - V_R)^2}{2} \right)$$

- Bias power plus a preload will adjust $f_{SW}(sb)$ to approach $f_{SW}(min)$, 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





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

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

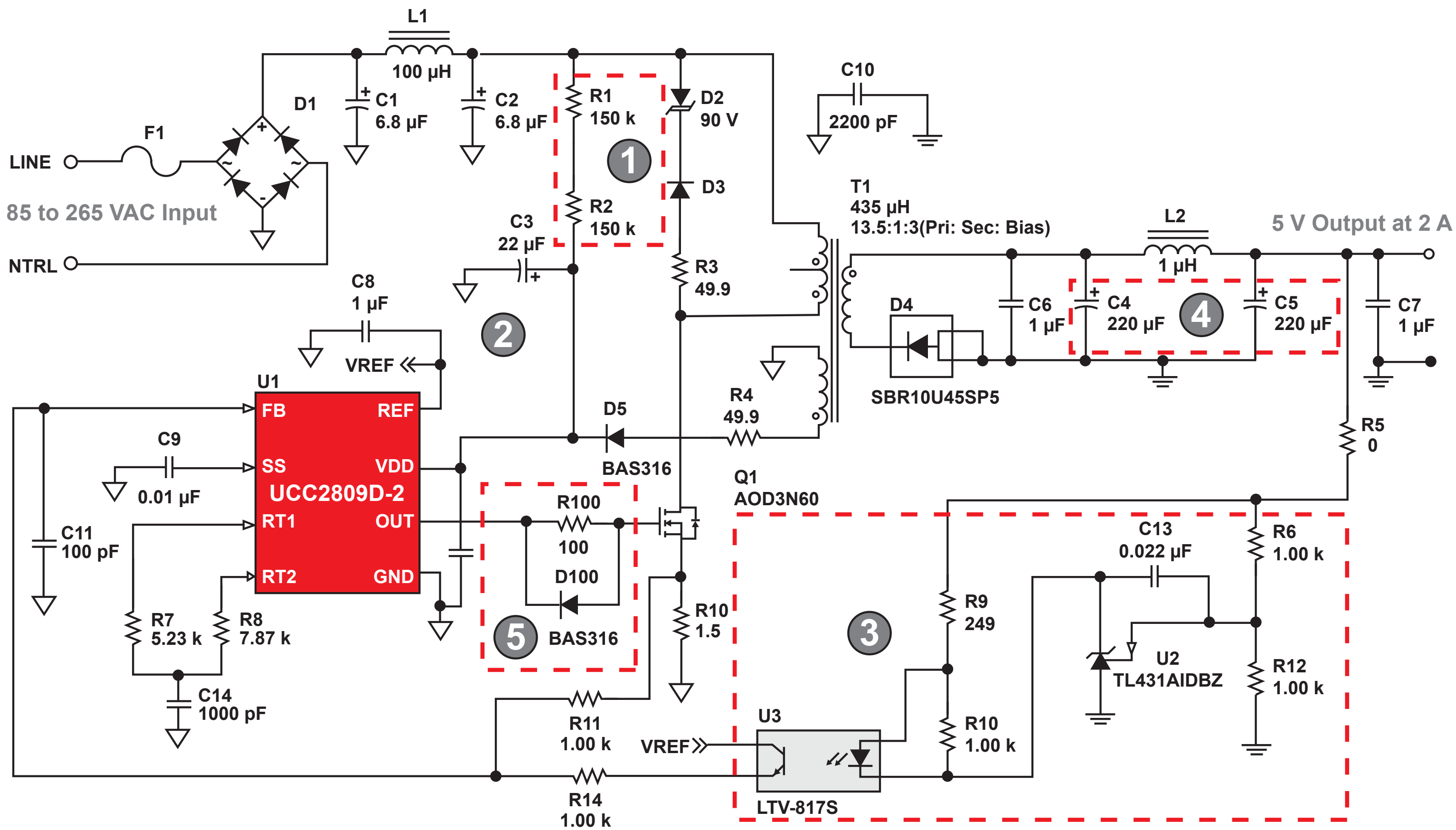
Control Methodologies Evaluated:

- 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:

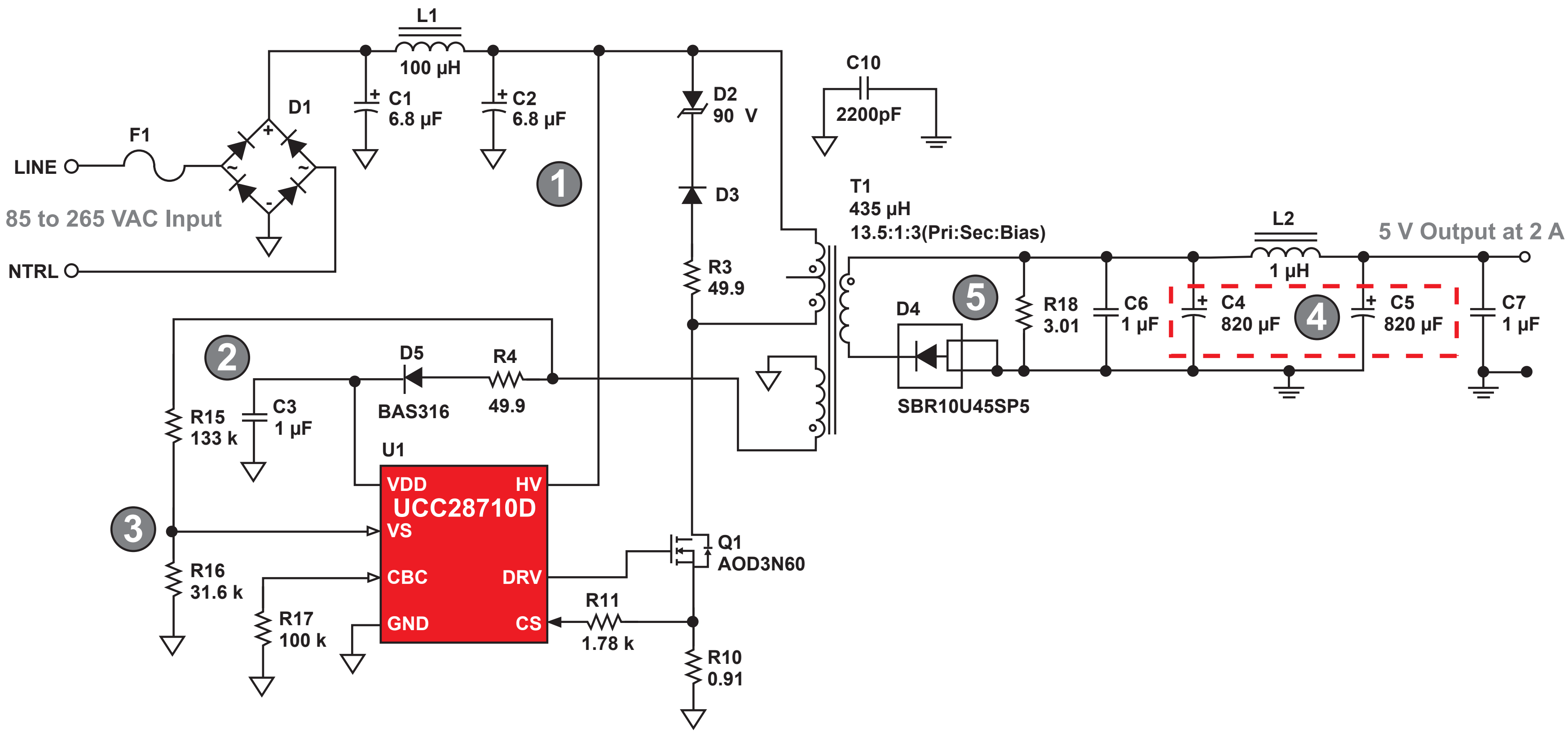
- All designs operate at ~100 kHz at maximum load
- Same transformer, FET, diode used on all designs

DCM/FF/Opto Example



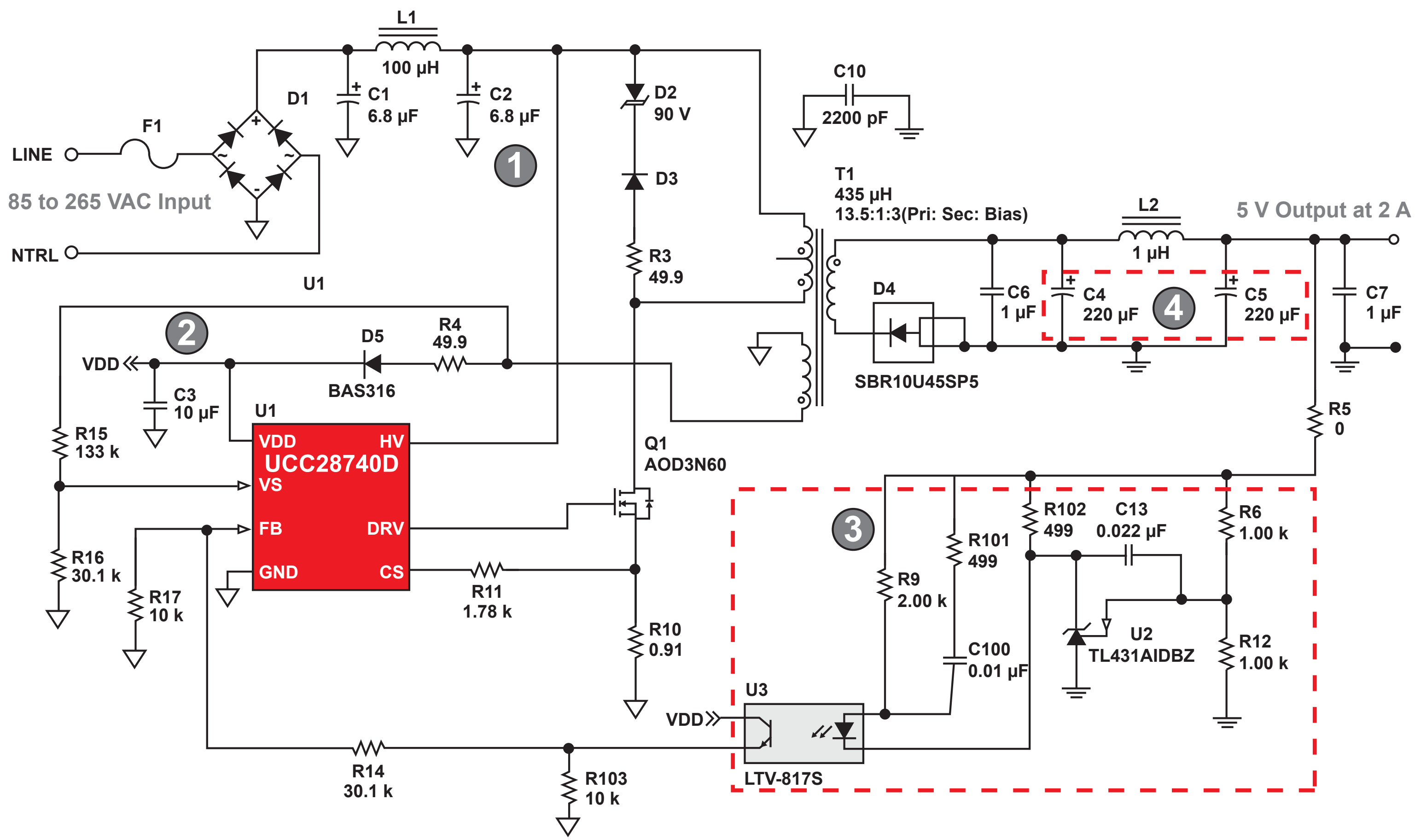
1. Start-up resistors increase standby power
2. Large bias cap; factors include I_{DD}, opto current, UVLO hysteresis
3. TL431 and opto-coupler for regulation
4. Faster loop response allows smaller output caps
5. Minimum on-time requires turn-on resistor at no load operation

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

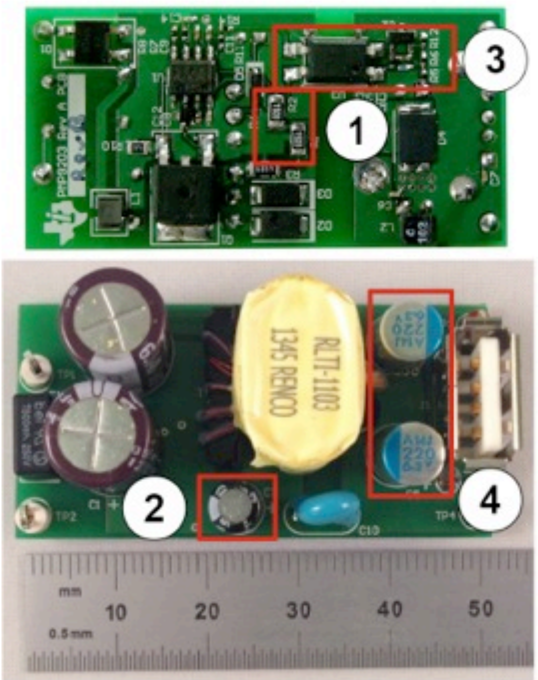
DCM/VS/Opto Example



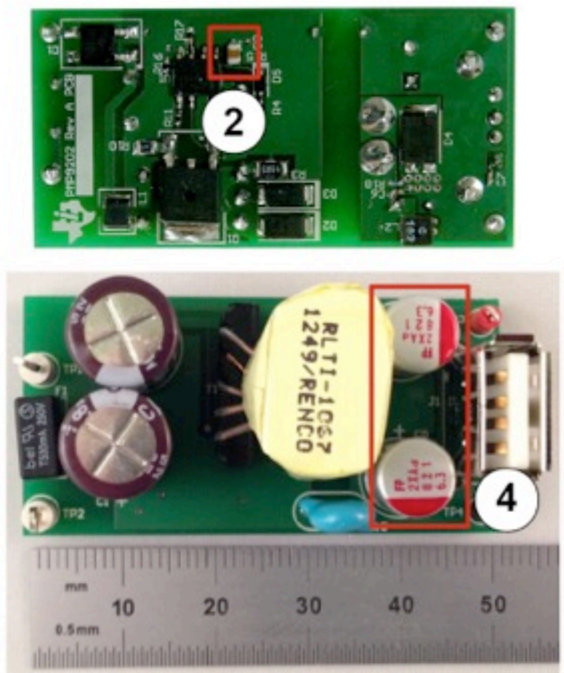
1. No start-up resistors (lower standby power)
2. Medium sized bias capacitor
3. TL431 and opto-coupler regulation
4. Faster loop response allows smaller output caps

Photographs

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



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



DCM/VS/Opto
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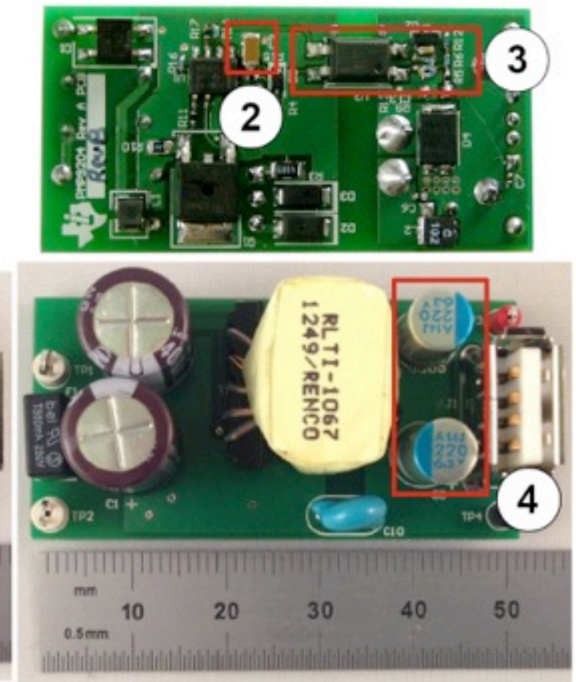
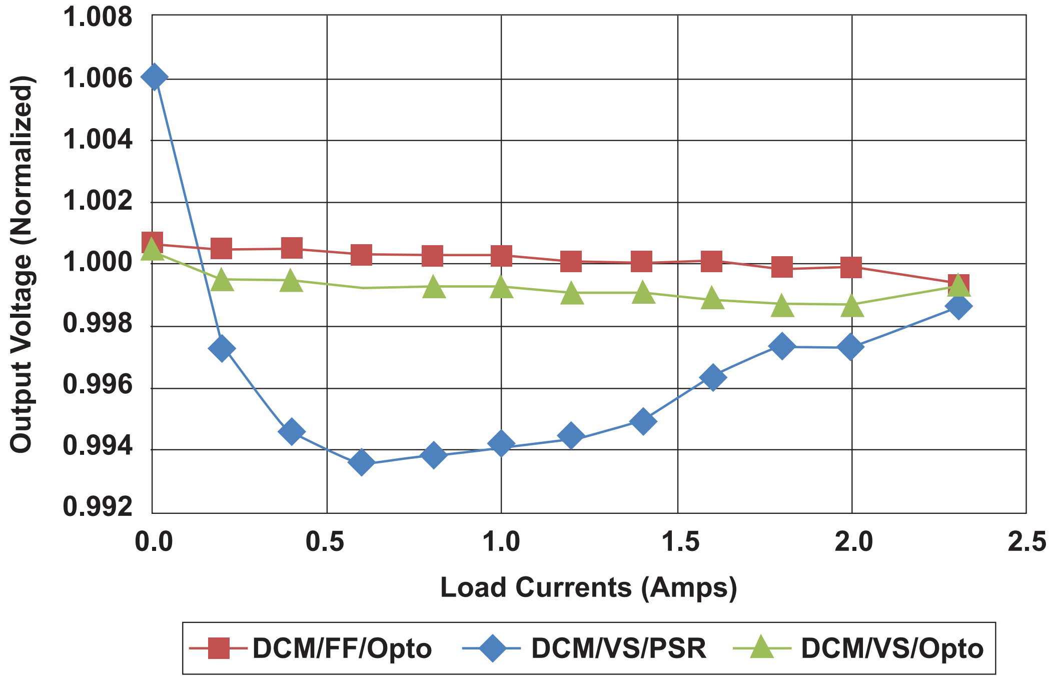


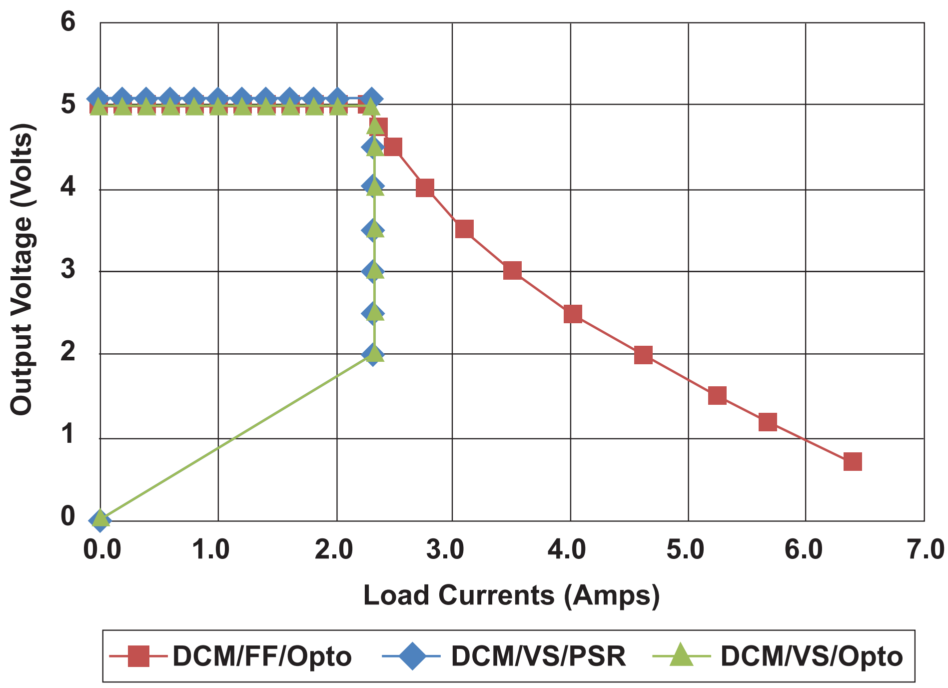
1. Start-up resistors
2. Bias capacitor
3. TL431 and opto-coupler
4. Bias capacitor

Load Regulation



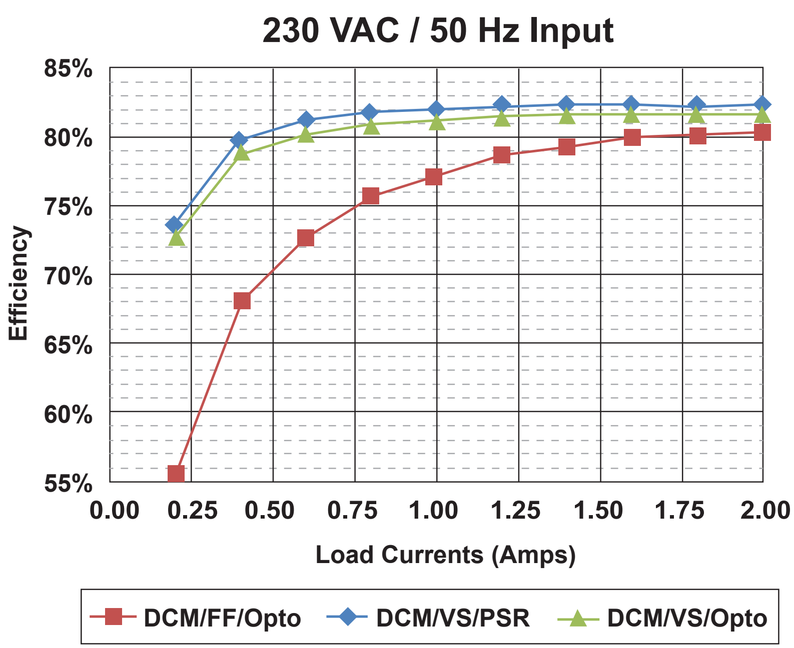
- TL431 and opto-coupler provides excellent load regulation
- PSR uses cable-drop compensation
  - Compensates for resistive drops on the secondary side
  - Keeps load regulation within +/-1%

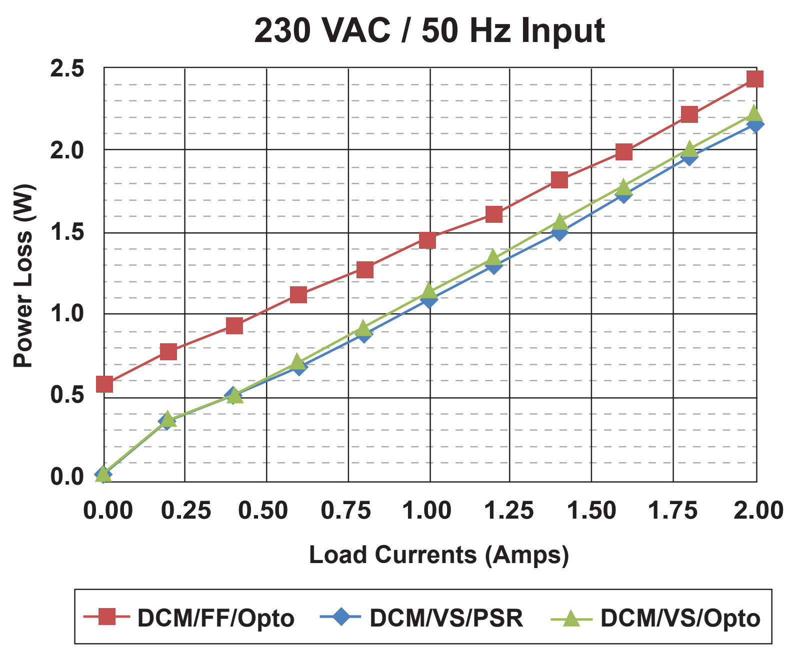
Overload Protection



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

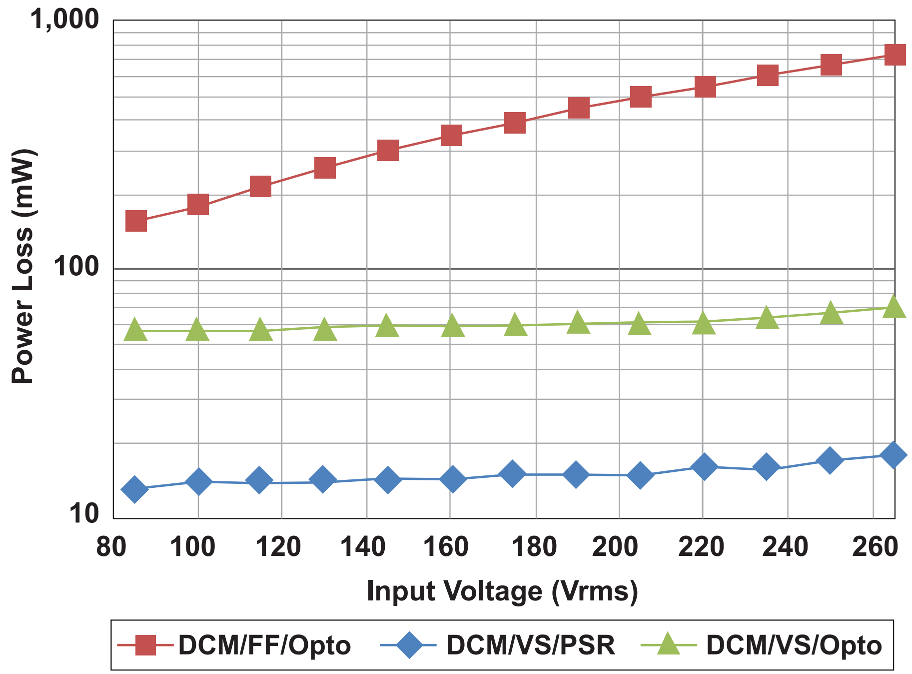
Efficiency





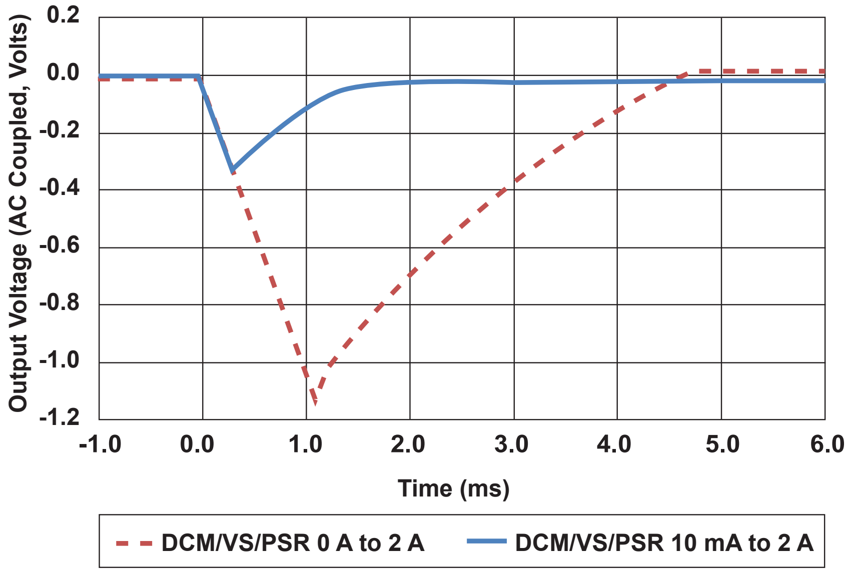
- All designs achieve >80% efficiency at max load
- DCM/VS controllers provide better efficiency at low to medium loads
  - Due to reduced frequency operation
- Start-up resistors have major impact at higher input voltages

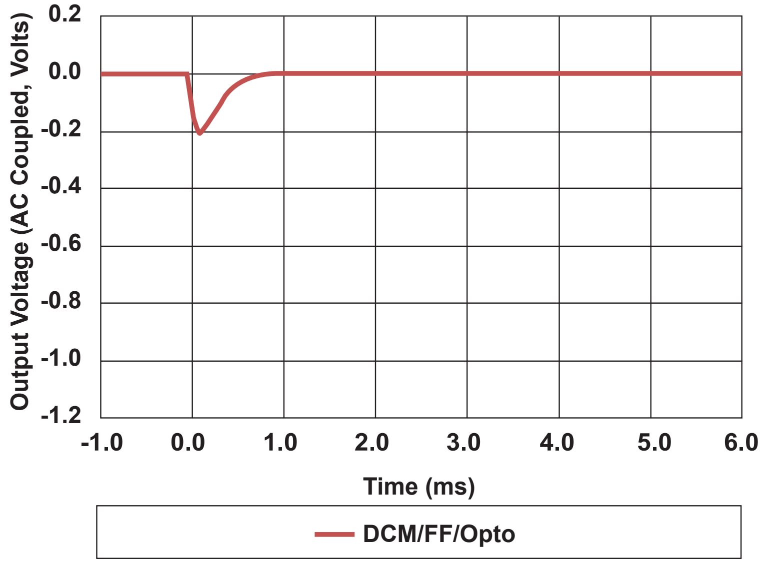
Standby Power Consumption



- 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

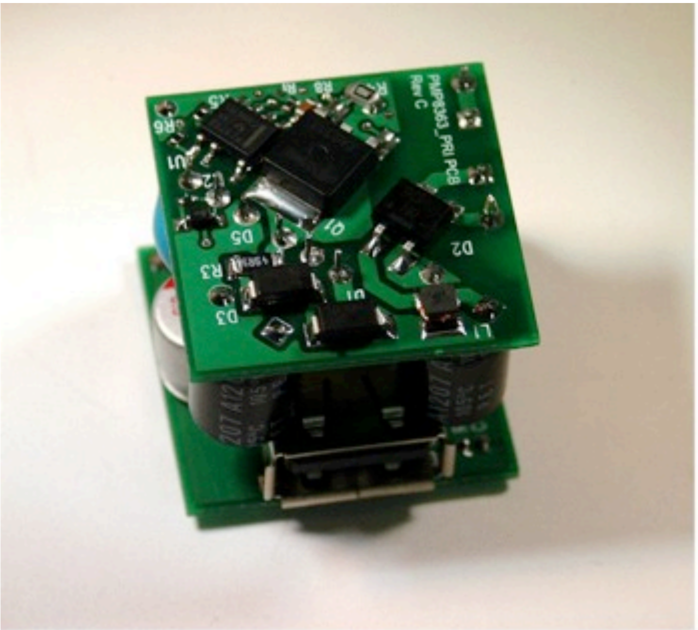
Load Transient Response

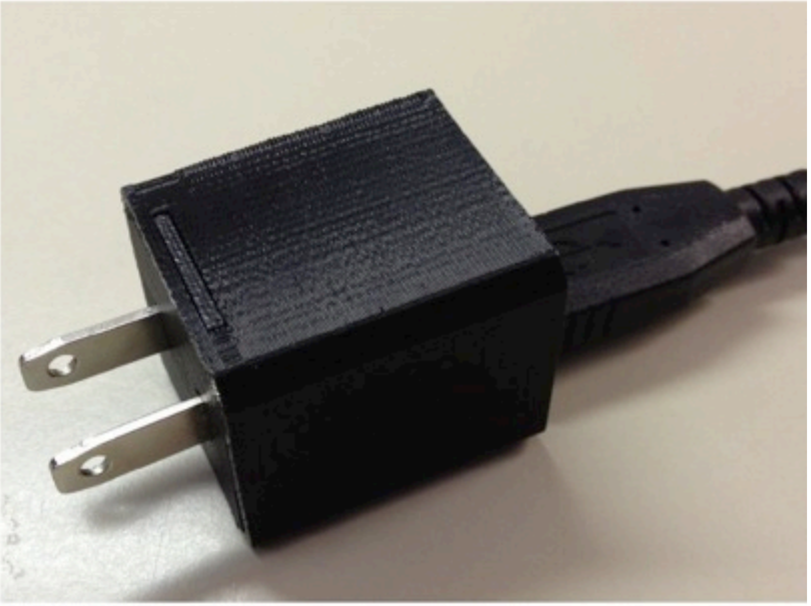




- PSR response varies
  - Dependent on when in the switching cycle the transient hits
  - Starting at 0 A vs. a few mA makes a big difference
- TL431 and opto-coupler response is predictable
  - Dependent on output capacitance and bandwidth

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

	DCM/FF/Opto	DCM/VS/PSR	DCM/VS/Opto
Output Voltage Accuracy	+/-2% ★	+/-5%	+/-2% ★
Load Regulation	+/-0.1% ★	+/-0.6%	+/-0.1% ★
Max Load Eff. (115 VAC / 230 VAC)	82.0% / 80.4% ★	82.2% / 82.5% ★	81.3% / 81.7% ★
Standby Power (115 VAC / 230 VAC)	216 mW / 584 mW	14 mW / 16 mW ★	57 mW / 64 mW ★
Load Transients (0 A to 2 A)	-200 mV ★	-1100 mV	-200 mV ★
Current Regulation	Not Provided	+/-5% ★	+/-5% ★
# of Components	41	27 ★	37
Relative Cost	Low	Lowest ★	Low