A Fresh Approach to Switching Regulator Topologies and Implementations

Global Power Seminar 2006

Agenda

- Switching Topologies Overview
- Off-Line Regulators
  - FPS
  - FPS Quasi-resonant Mode
  - FPS Buck & SEPIC Modes
- LED Lighting
  - Off-line
  - DC-DC
Switching Topologies Overview

Charge Pumps
- Simple & moderate cost
- Can be step up/down or invert
- Require only resistors and capacitors
- Noise performance is architecture dependant
- Issues include:
  - Limited choices for $V_{out}$ vs. $V_{in}$
  - Can be noisy
  - Limitations on output power

Inductor Based
- Can be step up/down or invert
- Can handle a wide range of input and output voltages
- Generally higher cost
- Can obtain high current levels
- Issues include:
  - Need for magnetics
  - Board layout can be critical.
  - Require more components than charge pumps
Simple Single Output, Single Inductor Topologies

**Buck**
- \( M(D) = D \)

**Boost**
- \( M(D) = 1/(1-D) \)

**Buck Boost**
- \( M(D) = -D/(1-D) \)

M(D) vs. D relationship assumes Continuous Conduction Mode

D = Duty Cycle on horizontal axis, M(D) = voltage conversion ratio, on vertical axis

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Simple Single Output, Dual Inductor Topologies

**CUK**
- \( M(D) = -1/(1-D) \)

**SEPIC**
- \( M(D) = D/(1-D) \)

M(D) vs. D relationship assumes Continuous Conduction Mode

D = Duty Cycle on horizontal axis, M(D) = voltage conversion ratio, on vertical axis
Simple Transformer-Based Topologies

Forward
\[ M(D) = \frac{D}{N} \]

Flyback
\[ M(D) = \frac{1}{N(1-D)} \]

In the forward, the transformer is a true transformer and (hopefully) stores no energy.

In the flyback, the transformer is really coupled inductors and stores energy.

M(D) vs. D relationship assumes Continuous Conduction Mode

D = Duty Cycle, M(D) = voltage conversion ratio, N is the transformer turns ratio, always >1

Conduction Modes and Control Modes

- Conduction Modes
  - Discontinuous – current in the inductor remains at zero at some time in the cycle
  - Continuous – current in the inductor NEVER remains at zero at some time in the cycle
  - Systems can operate in both continuous or discontinuous modes depending on load and input voltage

- Control Modes
  - Take the output voltage, compare with a reference & feed the difference back to control the duty cycle
  - Voltage Mode – error voltage directly controls the duty cycle
  - Current Mode – error voltage controls the current through the switch
Flyback Converter – Discontinuous Conduction Mode (DCM)

![Diagram of a flyback converter in DCM mode with key components labeled: Vin, T1, SW1, VSW, ISW, IR, Vin+nVo, VO, R_L, C1, and the waveforms showing the switch control and current paths.]

Flyback topology - circuit and waveforms, continuous conduction mode (CCM)

![Diagram of a flyback converter in CCM mode with key components labeled: Vin, T1, SW1, VSW, ISW, IR,Vin+nVo, VO, R_L, C1, and the waveforms showing the switch control and current paths.]

Primary Inductance value is larger than a comparable DCM system.
Discontinuous vs. Continuous Mode

- Continuous – lower peak currents
  - Lower conduction losses
  - Smaller input filter required to reduce EMI
  - Bigger transformer inductance
  - Higher cost fast recovery diodes required on the secondary side

- Discontinuous – higher peak currents
  - Higher $I^2R$ losses, Bigger core/Skin Effect losses
  - Bigger Input Filter to reduce EMI
  - Smaller transformer inductance
  - Lower cost secondary side rectifier diodes

40W, UK voltage SMPS, DCM
- $L_p = 350\mu H$
- $I_{pk} = 1.7A$
- Switch conduction loss = 1.3W

40W, UK voltage SMPS, CCM
- $L_p = 1mH$
- $I_{pk} = 1.1A, I_{min} = 0.6A$
- Switch conduction loss = 1.1W

Control Modes: Voltage or Current Mode

Voltage mode
- The PWM clock turns the switch on. An internally generated ramp is compared to $V_{fb}$ to determine when to turn the switch off
- In voltage mode, the output voltage is compared to a reference and controls the PWM duty cycle directly
- If the output is too low, the PWM duty cycle is increased, which, in turn, causes the output voltage to increase
- Hence, the feedback voltage directly controls the duty cycle
Control Modes: Voltage or Current Mode

Current Mode
- Similarly to voltage mode, the output voltage is compared to a reference and the difference fed back as Vfb.
- In current mode, the clock turns the switch on.
- When the switch current crosses a threshold, the switch is turned off. The threshold is set by VFB.
  - In this way, the maximum current in the switch is limited for each PWM pulse: "pulse-by-pulse current limit"
- Due to the interaction of the voltage and current feedback loops, the operating threshold is variable:
  - If the output is too low, the current threshold is increased, which increases duty cycle
  - Since di/dt = V/L, the system will automatically compensate for changes in V with no change required in VFB

Voltage Mode vs. Current Mode
- Current mode has better line regulation.
  - The control loop does not have to respond to a change in line voltage. The drain current slope is defined by Vin/L. Hence if Vin increases, di/dt also increases and the duty cycle is automatically changed with no change in Vfb.
- Voltage mode systems often have greatly differing dynamic loop parameters between CCM and DCM resulting in different stability and different transient response.
  - A CCM systems will enter DCM at low loads and/or high input voltages
- Current mode automatically limits the current in the primary winding
  - This reduces the maximum current specifications for the transformer, the line filter and the rectifier, saving costs
  - Easy to implement many protection functions: over-load, secondary or transformer shorts etc.
- Voltage Mode allows duty cycles greater than 0.5
  - Current mode requires slope compensation to do this
- Voltage mode has improved load regulation
  - The current loop can appear to initially go the wrong way
- Voltage mode does not require current sensing
  - No power loss or expense due to current sensing (assumes that lossless sensing is not used).
- Voltage mode requires a higher order of loop compensation
Fairchild Power Switch

Fairchild Power Switch (FPS™) – What is it?
### Green FPS™ Portfolio

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<th>Green FPS™ Part Number</th>
<th>Output Power (W)</th>
<th>Switching Frequency (kHz)</th>
<th>TSD</th>
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**Devices with power ranges from 7 to 210W (230VAC +/- 15%)**

### Features of Fairchild Power Switch

- **Current mode operation (FSD2XX are voltage mode)**
  - Directly limits current flowing through the transformer
- **Fully avalanche-rated and 100% tested SenseFET**
- **Lossless current sensing**
- **Cheaper snubber network**
- **More robust against transients**

**Protection**

- **Over Voltage Protection (OVP)** - protects against output over voltage due to open circuit opto for example.
- **Over Temperature Protection (OTP)** – self explanatory
- **Over Load Protection (OLP)** – shuts down in the event of over-load
- **Abnormal Over-current (AOCP)** – protects against short circuit secondary diodes and transformer shorts

Together, these benefits lead to a lower cost, more reliable system solution
Block Diagram of FSDM0365RN

Protection block

Typical Single Output FPS Schematic

Transformer & Secondary side

RCD Snubber

Input EMI filtering & bridge rectifier

Power switch

Reference & Feedback
The built-in start-up provides trickle current to charge Vcc until the FPS supply voltage reaches a preset voltage threshold called V\textsubscript{\text{start}}.

Switching then starts and the peak current allowed is increased in fixed increments over time.

Soft start advantages:
- Helps prevent high currents during start-up from damaging the components in the SMPS.
- Limits output voltage overshoots.

Features: Burst Mode Operation

- In standby mode, outputs draw very little to no load current.
- V\textsubscript{fb} is proportional to load.
- When the feedback voltage goes below V\textsubscript{BURSTH} threshold, switching continues at a fixed current driving V\textsubscript{FB} down further.
- When the feedback voltage goes below V\textsubscript{BURSTL} threshold, switching stops in the FPS device, saving considerable power.
- Depending on load current, the output voltages will eventually fall causing the feedback voltage to increase.
- Once the feedback voltage crosses V\textsubscript{BURSTH} threshold, switching starts again and the process repeats.
• Fixed frequency oscillators generate EMI (Electromagnetic Interference) in a narrow band of the frequency spectrum
• Fairchild’s latest FPS devices modulate its frequency over a ±4kHz frequency range
• EMI is thus spread over a wider range of frequencies
• Allows simple EMI filters to be employed for meeting worldwide EMI requirements
• Refer to Application Note AN-4145: Electromagnetic Compatibility for Power Converters for additional information

Features: Frequency Modulation for EMI

Over-Load Protection

• The switching current is defined by \( V_{\text{FB}} \) which quickly increases with output power, as \( C_{\text{FB}} \) is charged by \( I_{\text{FB}} \).

• Once \( V_{\text{FB}} \) passes 3V at T1, the device is switching at maximum current & \( V_{\text{FB}} \) cannot rise any further

• \( V_{\text{FB}} \) continues to rise slowly, charged by \( I_{\text{DELAY}} \) since D1 is now reverse biased

• Once \( V_{\text{FB}} \) passes 6V at T2, the device shuts down

• \( V_{\text{CC}} \) will now fall and once it passes the lower UVLO threshold, the device will attempt auto-restart

• OLP is therefore timed allowing short term transient over-loads without shut-down. Delay times can be set by \( C_{\text{FB}} \) value. Extra delay can be introduced with a zener & capacitor in parallel with \( C_{\text{FB}} \).

Internal OLP block, \( C_{\text{FB}} \) is external.
\[
I_{\text{FB}} = 900\mu A
\]
\[
I_{\text{DELAY}} = 5\mu A
\]
Normal Operating Waveforms

Traces from top to bottom:
- Drain voltage
- Drain current 0.5A / div
- Voltage across secondary diode of 24V output

Input Voltage: 195VAC  
Input Voltage: 265VAC

Note: The switch current is the same in both cases. Therefore, $V_{fb}$ will be the same.

Switching Waveform at a Minimal Load

Input Voltage: 230VAC

Traces from top to bottom:
- Drain voltage
- Supply voltage
- Feedback voltage

- The power loading is very much reduced and so the duty cycle is small
- The system is clearly running in DCM
- The ripple- once the secondary side has finished conducting- is normal and is caused by resonance of stray capacitance in the switch and the primary inductance
**Quasi-Resonant Operation**

*quasi*
adj : having some resemblance; "a quasi success"; "a quasi contract" – "somewhat resonant"

In our case, by strategically adding an L-C tank circuit to a standard PWM power supply, we can utilize the resonant effects of the tank to “soften” the transitions of the switching device. This will help reduce the switching losses and EMI associated with hard switching converters.

The fact that we are utilizing the resonant circuit *only* during the switching transitions to an otherwise standard square wave converter gives rise to the name Quasi-Resonant!

**Flyback Parasitics**

- The MOSFET switch has parasitic capacitances
  - \( C_{\text{oss}} = C_{\text{DS}} + C_{\text{DG}} \) It is critical to switching losses in hard switching converters
  - \( C_{\text{iss}} = C_{\text{GS}} + C_{\text{DG}} \)

- The transformer has a leakage inductance. This can be modelled as a (hopefully) small inductance in series with the primary

- The transformer also has a winding capacitance but this is often ignored.

- \( C_{\text{TOT}} = \) total parasitic capacitance
- \( L_L = \) leakage inductance
A Closer Look at the Drain Resonances

- There are two resonances of interest
  1. \( C_{TOT} \) resonating with \( L_L \) at primary switch off
  2. \( C_{TOT} \) resonating with \( L_P \) at secondary switch off
     Note: this is not present in CCM

- Note the effect of the Snubber at switch-off

Now Let’s Turn This into a QRC System

1. Remove the Snubber
   Now we have a real problem since we risk causing the switch to avalanche. The \( C_{TOT}, L_L \) resonance voltage is huge

\[
V^2 = I_{PK}^2 \times L_L / C_{TOT}
\]

Note: without the snubber the switching device would avalanche and be destroyed.
Now Let’s Turn This into a QRC System

2. Add extra capacitance across the switch
   - $C_{TOT}$ is increased so $V$ has decreased
   - The frequency of both resonances has also decreased
   - The technique is to increase the capacitance until the peak drain voltage is acceptable. The lower the capacitance the lower the switching loss but the higher the drain voltage.

More on Turning This Into a QRC System

3. Adjust the switching frequency & duty cycle by adjusting the point at which the device switches on
   - Now the switch turns on at the bottom of the $C_{TOT}\times L$ resonance
   - Since the switch off edge is slowed, we have soft switching reducing EMI.
   - Since $V_{DS}$ is reduced or zero at switch on, we have lower $C_{OSS}$ switching losses and reduced EMI.
   - A QRC system has variable switching frequency defined by load and input voltage
     - Since the DC link will always have some ripple, even with constant load, the switching frequency will be modulated by the ripple helping to spread EMI energy.

Note: In reality, the Snubber spike would probably be smaller but this is shown for clarity.
To detect the drain voltage valley with a Fairchild FSCQ device, the V_{CC} bias winding is monitored.

First, \( R_{SV1} \) and \( R_{SV2} \) should be chosen so that the divided signal is less than the OVP trip point of 12 V, typically 3-4V less.

Next, \( C_{SV} \) needs to be selected such that the decay of the sync waveform ensures it passes the sync threshold when the drain voltage is at the bottom of its resonance.

Sync pin components selected correctly

The sync pin voltage passes through the threshold at the minimum of the \( C_{TOT}, L_P \) resonance

Switching occurs at minimum or zero \( V_{DS} \)
A Limitation of QRC Mode

- The limitation
  - As the load decreases or input voltage increases, the switching frequency increases
  - When the system reaches its maximum switching frequency, it starts to cycle skip leading to reduced regulation
  - Alternatively we could end up with a minimum frequency within the audio band.

- The solution
  - As the system approaches an upper limit for the switching frequency, switch on the second minimum
  - Switching frequency will drop allowing the load to further decrease without cycle skipping

Extended Quasi-Resonant Switching

- Fixing the QRC limit
  - At low power levels, the device will operate in extended QRC
  - As the output power falls, the switching frequency increases
  - Once the frequency reaches the upper limit of 90kHz, extended QRC operation takes over
  - The device now switches on the second minimum and the switching frequency drops
  - The same effect can be seen as input voltage rises
  - When the device goes into extended QRC mode, the switching frequency decreases, allowing more range for it to increase before cycle skipping occurs.
Non-Isolated Topologies

Non-Isolated Topologies: Buck vs SEPIC

- Buck – can only step down
  - High Side Switch
    +12V output, 1 inductor

- SEPIC – can step up or down
  - Low Side Switch
    +12V output, 2 inductors, 1 high voltage capacitor
  - The current ripple on the SEPIC can be minimized by having large inductor.
FSDL0165: Buck Mode Implementation

Buck Mode Operation – the On Time

Note: the FPS is operating as a high side switch.
Buck Mode Operation – the Off Time

Test Results for FSDL0165 Buck Board

- Low load input power
  - Highest value 370mW at 3°C, 265V
  - Minimum load was set to 10mA

- Efficiency
  - Exceeds 76% over temperature and voltage for loads of 100mA, 200mA and 300mA

- Efficiency changes
  - Best at high temperatures.
    - Core losses which decrease with temperature dominate over conduction losses which increase.
  - Best at mid voltages
    - Worse at low voltages. \( R_{DSS} \) losses increase.
    - Worst at high voltages (switching losses dominate)

- Accuracy
  - 14.8V – 15.5V, -1.3% to +3.3%
  - (0-300mA load, full temperature range)
  - Device variations not included

- The FSDL0265 and FSDL0365 devices can be used for higher power levels
The boost converter limitation is that $V_{OUT}$ must always be greater than $V_{IN}$ since there is a DC path between input and output.

The SEPIC removes this limitation by inserting a capacitor between the inductor and the rectifier to block the DC path.

However, the rectifier anode must be connected to a known potential by $L_2$.

So what's the advantage of SEPIC since it contains an additional inductor and capacitor?

- $V_{OUT}$ can be above OR below $V_{IN}$
- Better EMC – more of this later
- Potentially lower cost – more of this later

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**FSDL0165 SEPIC Implementation**

Advantages:

- Input current may be continuous => choose large $L_1$
- Switching losses are smaller compared to buck topology
- Wide input and output voltage range is possible

Note: this application is available as a completed evaluation board.
SEPIC Converter: On Time Current Flow

\[ I_{\text{dmax}} = I_{\text{in}} + I_{\text{out}} + \frac{(\Delta I_{L1} + \Delta I_{L2})}{2} \]
Buck vs. SEPIC Comparison

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For similar specified converters, the performance is similar

Input Switching Current Harmonics

- In all converters, the input switching current is provided by the DC link capacitor. It’s not perfect, so this generates a voltage:
  - \( V = I_{sw} \times ESR \)

- The buck mode switching current is a large impulse.
  - It is always discontinuous and contains a high harmonic content.

- The SEPIC mode switching current is a small saw-tooth.
  - It is continuous and contains a low harmonic content.

- Hence, the EMI is reduced

- It may be possible to meet EMI requirements without the use of an input filter and hence offset the cost of the extra capacitor and inductor in the SEPIC

- Hence, cost is reduced since an EMI filter often costs more than the extra inductor and capacitor required by the SEPIC.
The two plots show the EMI spectra of the SEPIC (left) and the buck board (right). No extra EMI filtering was used. Peak power was measured.

- The SEPIC is very close to meeting the EMI levels shown.
- The buck is well above the limits and needs extra LC filtering
- These results are to be expected from the large differences in the peak currents
Basic Control Circuit

Isolated Current Source with FPS

- Standard voltage regulator with KA431
- Low cost current regulator with bipolar transistor
Isolated Current Source with FPS

- Application: LED Driver
- Application Note: AN-4138

SEPIC Converter for LED lighting
Fairchild’s LED Drivers & DC-DC Converters for Low Voltage Applications

• Fairchild’s extensive state-of-the-art LED driver family provides designers with a multitude of LED driver choices—including the most popular options and features for various lighting applications. These low-dropout drivers provide a complete backlighting solution for portable devices.

Fairchild’s LED Drivers & DC-DC Converters for Low Voltage Applications

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LED Drivers Product Portfolio

Fairchild’s LED drivers save space, reduce part count, and provide uniform brightness. These LED drivers can regulate the LEDs either directly from the battery or through a DC/DC converter, and come in small (SC-70, MLP, and TSOT) packages to fulfill even the smallest PCB area requirements.

<table>
<thead>
<tr>
<th>Part Number</th>
<th>Number of Channels</th>
<th>LEDs per channel</th>
<th>Current (mA per channel)</th>
<th>Brightness control method</th>
<th>Input Voltage</th>
<th>Boost / Method</th>
<th>Dropout current (max uA)</th>
<th>Max Efficiency</th>
<th>Packages</th>
</tr>
</thead>
<tbody>
<tr>
<td>FAN5602</td>
<td>4</td>
<td>4</td>
<td>600</td>
<td>A, P</td>
<td>Unregulated / battery</td>
<td>Yes / charge pump</td>
<td>1 85%</td>
<td>MLP 3x3</td>
<td>MLP 3x3</td>
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<td>FAN5603</td>
<td>5</td>
<td>5</td>
<td>100</td>
<td>A, P</td>
<td>Unregulated / battery</td>
<td>Yes / charge pump</td>
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<td>MLP 3x3</td>
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<td>6</td>
<td>50</td>
<td>A, P</td>
<td>Unregulated / battery</td>
<td>Yes, inductor</td>
<td>1 85%</td>
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<td>SOT-23</td>
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<td>1</td>
<td>20</td>
<td>D,A,P</td>
<td>Unregulated / battery</td>
<td>Yes, inductor</td>
<td>1 85%</td>
<td>SOT-23</td>
<td>SOT-23</td>
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<tr>
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<td>4</td>
<td>20</td>
<td>D,P</td>
<td>Unregulated / battery</td>
<td>Yes, adaptive charge pump</td>
<td>2 92%</td>
<td>MLP 4x4</td>
<td>MLP 4x4</td>
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<td>FAN5607</td>
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<td>D,P</td>
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<td>Yes, adaptive charge pump</td>
<td>2 92%</td>
<td>MLP 4x4</td>
<td>MLP 4x4</td>
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<tr>
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<td>2</td>
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<td>Not required</td>
<td>1 91%</td>
<td>MLP 3x3</td>
<td>MLP 3x3</td>
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<tr>
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<td>4</td>
<td>40</td>
<td>A, P</td>
<td>Regulated</td>
<td>Not required</td>
<td>1 90%</td>
<td>SC70-6, SOT-8</td>
<td>SC70-6, SOT-8</td>
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<td>SC70-6, SOT-8</td>
<td>SC70-6, SOT-8</td>
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<td>SC70-6, SOT-8</td>
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<td>60</td>
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<td>SC70-6, SOT-8</td>
<td>SC70-6, SOT-8</td>
</tr>
</tbody>
</table>

* Brightness Control Method: D=Digital, A=Analog, P=PWM
**FAN5606: Serial LED Driver**

**Features**
- Drives up to six LEDs at 20mA constant current
- Digital, analog or PWM brightness control
- 2.7V to 5V input voltage range
- Adaptive output voltage for high efficiency
- Built-in current-regulated DC/DC boost
- Soft-start
- Built-in Schottky diode
- Single resistor current set in analog mode
- LED short circuit protection
- Shutdown current <1µA
- Small footprint 8-lead 3x3 MLP

**Applications**
- Portable video devices
- Cell phones
- Digital still cameras (DSCs)
- PDAs

---

**FAN5608: Dual Serial LED Driver**

**Features**
- Drives 2x6 LEDs at 20mA constant current
- Digital, analog or PWM brightness control
- 2.7V to 5V input voltage range
- Adaptive output voltage for high efficiency
- Built-in current-regulated DC/DC boost
- Accurate current matching between LED strings
- Soft-start
- Built-in Schottky diode
- Single resistor current set in analog mode
- LED short circuit protection
- Shutdown current <1µA
- Small footprint 8-lead 3x3 MLP

**Applications**
- Portable video devices
- Cell phones
- Digital Still Cameras
- PDAs
FAN5331 - 20V, 1A Boost OLED Driver / DC-DC Converter

**Features**
- VIN = 2.7V to 5.5V
- 1A peak switch current
- Adjustable output voltage
- 50mA @ 15V
- 1.6MHz operating frequency
- Low noise PWM operation
- Cycle-by-cycle current limit
- Over-voltage protection
- 5-lead SOT-23 package

**Applications**
- Portable video devices
- Cell phones
- Hand Held computers
- Portable electronic equipment
- Digital Cameras

---

FAN5332 - 30V, 1.5A Boost OLED Driver / DC-DC Converter

**Features**
- VIN = 2.7V to 5.5V
- 1A peak switch current
- Adjustable output voltage
- 75mA @ 20V easily achieved
- 1.6MHz operating frequency
- Low noise PWM operation
- Cycle-by-cycle current limit
- Over-voltage protection
- 5-lead SOT-23 package

**Applications**
- Cell phones
- Hand Held computers
- Portable electronic equipment
- Digital Cameras
FAN5333A/B
20V @ 75mA Boost LED Driver

Features
• $V_{IN} = 1.8V$ to 5.5V
• 1A peak switch current
• Adjustable output voltage
• 75mA @ 20V
• 0.1V feedback voltage
• High Frequency PWM Dimming
• 1.6MHz operating frequency
• Low noise PWM operation
• Cycle-by-cycle current limit
• Over-voltage protection
• 5-lead SOT-23 package

Applications
• Torches
• Bicycle Front Light
• Portable electronic equipment
• Digital cameras

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For more information on Fairchild Power Switch, please visit [http://www.fairchildsemi.com/whats_new/fps.html](http://www.fairchildsemi.com/whats_new/fps.html)

For more information on LED Drivers, please visit [http://www.fairchildsemi.com/whats_new/led_drivers.html](http://www.fairchildsemi.com/whats_new/led_drivers.html)
Appendix 1 – Additional FPS operating waveforms

• When the device is switching, the current increases rapidly since the magnetic core is unable to reset each cycle

• The switch current is limited by the over-current protection and therefore the duty cycle is small

• $V_{fb}$ rises and the device shuts down when $V_{fb}$ passes the OLP threshold

Short Circuit Protection

Input voltage: 230V AC

Traces from top to bottom:
• Drain voltage
• Supply voltage
• 24V output
Secondary Diode Short Circuit

Input voltage: 230V AC

Traces from top to bottom:
- Drain voltage
- Supply voltage
- Feedback voltage
- Feedback voltage

- When the switch turns on, the current through the inductor ramps up very fast. This is because the inductance is effectively reduced to the leakage inductance only
- The on time is limited by the switch current limit which results in a very short duty cycle
- The magnetic core is unable to reset each cycle
- After a few cycles the device stops switching
- A long time-base measurement would show that $V_{cc}$ drops to the lower UVLO threshold and the device auto-restarts

Shorted Optocoupler LED

Input voltage: 230V AC

Traces from top to bottom:
- Drain voltage
- Supply voltage
- Feedback voltage
- Supply voltage

- Since the opto LED is shorted, no current can flow through the opto-transistor and $V_{fb}$ rises quickly to 3.5V
- At this point, the device is switching at maximum duty. $V_{cc}$ rises quickly and passes the over-voltage protection (OVP) threshold at 24V
- The device then stops switching and $V_{cc}$ starts to decay
- $V_{fb}$ continues to rise but this has no effect. Once $V_{cc}$ decays to the lower ULVO threshold the device auto-restarts and the cycle repeats
- Start-up is normal
Feedback Shorted to Ground

Input voltage: 230V AC

Traces from top to bottom:
- Drain voltage
- Supply voltage
- Feedback voltage
- Supply voltage

- The device tries to start as normal: $V_{cc}$ rises and passes the UVLO threshold
- The device then draws more current and tries to switch but cannot as $V_{fb}$ is grounded
- The $V_{cc}$ capacitor discharges because of the increased $V_{cc}$ current and falls below the lower UVLO threshold where the device tries to start again