Power Supply Design Seminar

Topic 1 Presentation:

High Power Factor and High Efficiency — You Can Have Both

Reproduced from
2008 Texas Instruments Power Supply Design Seminar
SEM1800, Topic 1
TI Literature Number: SLUP282

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Topic 1

High Power Factor and High Efficiency: You Can Have Both

Isaac Cohen and Bing Lu
Agenda

- Definition of power factor and discussion of the applicable standards
- Effect of the power factor on power-distribution losses
- Benefits of active PFC
- Effect of the input-voltage range on PFC efficiency
- Configurable PFC topologies
- The buck PFC: a solution for universal input-voltage applications
- Conclusions
Definition of Power Factor: A Quick Review

- \( PF = \frac{\text{Real Power}}{\text{Apparent Power}} \)

- \( \text{Real Power} = \frac{1}{T} \int_{0}^{T} v(t) dt \)

- \( \text{Apparent Power} = V_{\text{RMS}} \times I_{\text{RMS}} \)

- Definition valid for arbitrary current and voltage waveforms
Linear and Nonlinear Loads

◆ Sinusoidal source, linear load
  ■ Both the voltage and the current are sinusoidal but not in phase; power factor less than unity
  ■ PF known as: \( \cos(\Phi) \) or “displacement power factor”

◆ Sinusoidal source, nonlinear load
  ■ PF is determined by phase angle and harmonics
  ■ Harmonics increase apparent power, the power factor also less than unity
  ■ Reducing harmonics increases the power factor
Standards for Power-Factor Correction

- **EN61000-3-2**
  - Focuses on line-current harmonics
  - Four categories according to different end equipments
  - Most power supplies are Class D

- **Energy Star®**
  - Power supplies with greater than or equal to 100-W input power must have a true power factor of 0.9 or greater at 100% of rated load when tested at 115 V, 60 Hz

- Universal-input power supplies need to meet requirements of both standards
Power Factor and EN61000-3-2 Class D

Meeting EN61000-3-2 harmonic standard is not enough to meet the Energy Star power-factor requirement.

<table>
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<th>Harmonic Order (n)</th>
<th>75 W &lt; P &lt; 600 W Maximum Permissible Harmonic Current (mA/W)</th>
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<tr>
<td>3</td>
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<tr>
<td>5</td>
<td>1.9</td>
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<tr>
<td>7</td>
<td>1.0</td>
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<td>9</td>
<td>0.5</td>
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<tr>
<td>11</td>
<td>0.35</td>
</tr>
<tr>
<td>13</td>
<td>0.269</td>
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<tr>
<td>15 ≤ n ≤ 39</td>
<td>3.85/n</td>
</tr>
</tbody>
</table>

\[ PF = F_{\text{Displacement}} \times F_{\text{Distortion}} \]

\[ F_{\text{Displacement}} = 1 \]

\[ PF = \frac{I_1}{\sqrt{\sum_{n=1,3}^{39} I_n^2}} = 0.726 \]
Harmonics for Energy Star

- A power supply drawing square-wave line current is well within Energy Star PF limits but will fail the IEC harmonic-content standard

\[
\text{PF} = 0.9
\]

\[
I_{11} = 0.56 \text{ mA/W} > 0.35 \text{ mA/W}
\]
Meeting Both Standards

◆ The PFC circuit must increase the PF to the Energy Star limit AND attenuate the harmonics below the limits of EN61000-3-2
The Power Factor and the Power-Distribution Losses

- If the PF is low, an increase in RMS current is required to deliver a given amount of power.
Normalized Power-Distribution Losses

Where:

- $V_{\text{gen}}$ = Effective AC source voltage
- $R_{\text{w}}$ = Distribution wiring resistance
- $R_{\text{load}}$ = Load resistance

Diagram:

- Generator
- Wiring: $R_w = 0.05 \ \Omega$
- Load: $R_{\text{load}} = 1 \ \Omega$
Effect of the Power Factor on Power-Distribution Losses

- PFC reduces distribution losses
- Assuming 5% distribution loss, the system will break even if the efficiency of the PFC circuit is 0.953
Direct Benefits of PFC/Harmonics Attenuation

◆ Meet the requirements of EN61000-2-3 and Energy Star
◆ Higher power factor
◆ Allows higher power draw from 115-V lines
  ■ 0.5 PF = 719 W, 0.9 PF = 1294 W (intermittent rating)
◆ Reduced stresses on neutral conductors
◆ Improved electrical system distribution efficiency (Only if the PFC efficiency is high enough!)
◆ Reduced VA rating of standby power systems
Indirect Benefits of Active PFC/Harmonics Attenuation

- Facilitates power supply holdup
- Universal input voltage capability (85 to 265 VAC)
- Improved efficiency of downstream DC/DC converters
Active PFC/Harmonic Attenuation Circuits

◆ Most popular active PFC circuit: The boost converter

◆ This additional conversion stage adds power dissipation

◆ Efficiency of the PFC stage is strongly dependent on the difference between the input and the output voltage
To examine the effect of the difference between the input and output voltages on efficiency, we define the “Boost Factor” BF:

\[ BF = \frac{V_{\text{out}}}{V_{\text{in}(pk)}} \]
Analysis of the Boost PFC Efficiency

◆ A nonisolated converter is similar to an autotransformer

◆ Separate the power flow by separating the power transferred directly to the output from power processed by the PFC circuit

◆ Emulate the PFC boost converter by adding the output of a flyback converter ("ΔV converter") in series with the rectified line-input voltage

◆ The model is equivalent to a boost converter
The $\Delta V$ Converter

- A little algebra shows that the DC transfer function of the proposed circuit is identical to that of a boost converter.

![Diagram of the $\Delta V$ Converter]

$$V_{out} = V_{in} + \frac{D}{1-D} \times V_{in}$$

$$= \frac{V_{in}}{1-D}$$
Peak-Power Rating of the $\Delta V$ Converter as a Function of Input Voltage

![Graph showing the peak-power rating of the $\Delta V$ converter as a function of input voltage. The graph includes three curves, each labeled with a breakpoint factor (BF) and corresponding input voltage (V_in).]

- BF = 3.118 (V_in = 85 V)
- BF = 1.418 (V_in = 187 V)
- BF = 1 (V_in = 265 V)
Average-Power Rating of ΔV Converter as a Function of Input Voltage

- The average power delivered by the ΔV converter is a strong function of BF.
- An increasing BF also corresponds to an increase in boost-PFC size and cost.
Overall PFC Efficiency versus BF

- $\Delta V$ converter efficiency = 90%
Discussion of the Results

- As the boost factor increases, the converter processes more power and the efficiency decreases.

- Component ratings and converter efficiency are driven by the lowest operating Boost Factor.

- For “local” voltages:
  - Designed for Boost Factor of 1.417
  - $\Delta V$-converter average- and peak-power ratings are 40.1% and 58.9% of the PFC-stage output power.

- For universal input voltage:
  - Designed for Boost Factor of 3.118
  - $\Delta V$ converter average- and peak-power ratings are 73% and 136% of the PFC-stage output power.
Universal-Input Voltage Issues

◆ Must or preference?

◆ Logistics, commonality

◆ “Regional” products
  ■ HVDC bus voltage
  ■ BOMs for the PFC converter and the downstream DC/DC converter(s)

◆ Trade-offs
Improving PFC Efficiency: Reduce Boost Factor!

◆ Ideas:
  - Boost follower
  - Configurable PFC stage
    - Three-level PFC
  - Buck instead of boost PFC
**Boost-Follower PFC**

- Conventional PFC maintains same output voltage for different line voltages, the boost factor is 3.3 at 85-V input.
- Boost follower PFC changes its output voltage according to the AC line voltage (following AC line voltage).
- Boost factor is greatly reduced and efficiency can be improved but $V_{out}$ is not constant.
Boost-Follower PFC Implementation

- By adjusting the voltage-sensing divider network, output voltage can be changed with most off-the-shelf PFC controllers

"Simple circuitry gets that old PFC controller working in a boost-follower PFC Application," By Michael O'Loughlin
Design Considerations

◆ “Boost Follower” reduces BF but:

- Transformer turns ratio in the downstream converters must be lower, so:
  - Primary currents are higher, VA rating increases
  - Higher voltages on rectifiers, higher $V_f$
  - Larger filter inductor
  - Larger capacitors on the HV bus
Configurable Topologies

◆ Use identical components for both 115-V and 230-V inputs

◆ Same HVDC bus voltage

◆ Configuration on assembly line for 115 V or 230 V

◆ Nearly equal efficiencies for 115-V or 230-V operation
“Ideal” Configurable PFC

**High line-input configuration**

- At high line input, the MOSFETs, diodes, and inductors are in series
- Output voltage is equal to the peak of the high line voltage (same as conventional PFC)
- Equal stresses on the converter components at either “High” or “Low” line-input configuration!

**Low line-input configuration**

- At low line input, the MOSFETs, diodes, and inductors are in parallel
- Output voltage is only half the peak of the high line voltage
Boost Factor of Ideal Configurable PFC

- At “high” line-input condition, the BF and the output voltage are the same as for a conventional PFC.
- At “low” line-input condition, the BF and the output voltage are half the values of a conventional PFC.
“Real-Life” Solutions

◆ The “ideal” circuit is not practical
  ■ Voltage balancing for series devices
  ■ Driving circuit for series circuits

◆ Practical circuits will be less efficient than the ideal
Configurable Three-Level PFC

- High line-input condition: two boost PFCs are in series

- Low line-input condition: only one boost PFC is operating at each half line cycle

Note: Output-bus voltage does not change for different configurations.
Boost Factor and Efficiency Estimation

- Configurable three-level PFC maintains same output voltage for different line conditions
- At low line input, each boost PFC operates half-line cycle and the equivalent output voltage is half of the total PFC output voltage
- This reduced output voltage reduces the boost factor at low line input and improves efficiency
Benefits and Challenges

◆ Benefits

■ Reduced boost factor improves overall system efficiency

■ Three-level structure, a lower-voltage switches and diodes can be used to improve efficiency

■ At low line conditions, the bridge is reconfigured as a doubler (bridge diodes can be paralleled)

◆ Challenges

■ At low line input, each boost PFC only operates half of the line cycle (component utilization)

■ Devices referenced to different grounds: drive, current sensing

■ Voltage balancing on the output capacitors
The Buck PFC

- A buck converter can also shape the input current
- Handles least power at lowest input ("Buck Factor")
Idealized AC-Line Current with a Buck PFC

Low Line Input
(Normalized input current)

High Line Input
(Normalized input current)
Buck PFC and Prevailing Standards

- The buck PFC draws current only if the input voltage is higher than the output voltage.
- The optimal output voltage for universal input voltage is 80 V.
- Waveform is “ugly” – but passes both EPA and IEC standards.
Benefits of the Buck PFC

- Solves the problem of low efficiency at low input voltage
- Allows optimization of the downstream DC/DC converter
- Inherent inrush-current control
- “Gentler” on the HV diode than the boost converter it replaces
Efficiency of a 90-W Buck PFC versus the AC-Input Voltage
Conclusions

◆ PFC provides many benefits but adds losses that are strongly affected by the Boost Factor

◆ Reconfigurable-PFC topology is available that can reduce the effective BF and use the same components for both 115-V and 230-V lines—others to be invented?

◆ It remains to be seen if the pressure for ever higher efficiency will drive adoption of more complex topologies

◆ The buck PFC is an attractive solution for universal input voltages at power levels below 600 W
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